DECISION SUPPORT MODEL TO SELECT THE OPTIMAL MUNICIPAL SOLID WASTE MANAGEMENT POLICY AT UNITED STATES AIR FORCE INSTALLATIONS

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John Dulin

Table of Contents

List of Figures

List of Tables

AFIT/GOR/ENS/97M-22

Abstract

The United States Air Force has recently defined three objectives in developing strategies regarding the management of municipal solid waste at the base level. They are: (1) 50 percent reduction in total waste generated, from a 1992 baseline amount, by 1999; (2) 50 percent recycling of all waste generated, beginning in 1999; and, (3) a minimum cost program. With these objectives in mind, base environmental engineers must take appropriate actions in an effort to develop a program that meets these goals. Through consultations with base environmental managers, as well as research of the available literature, a decision support model was constructed to aid the decision maker in selecting a program that shows the best performance relative to these objectives. This model considers decisions regarding waste collection methods, waste reduction methods, and waste incineration. Sensitivity analysis is used to determine the most important variables in the model. Finally, the model and resulting analysis provide the decision makers with valuable insight concerning the selection and implementation of a municipal solid waste management policy.

Chapter I. Introduction

Background

In 1995, Americans generated over 300 million tons of garbage, hereafter referred to as municipal solid waste (MSW)(Steuteville, April 1996: 56). This waste was managed by one of four primary methods: landfilling, incineration, recycling, or composting (recycling of organic materials). About 63 percent of MSW generated in the United States is landfilled, 10 percent is incinerated and its ash is also landfilled, and the remaining 27 percent is either recycled or composted (Steuteville, April 1996: 56).

The United States Environmental Protection Agency (EPA) has long considered the problem of MSW management and disposal. In 1990 the Federal Pollution Prevention Act mandated that all federal facilities practice pollution prevention by reducing the waste at its source, recycling and composting as much waste as possible, treating the waste so as to prevent any harmful effects, and disposing of the remaining waste in as safe a manner as possible (USEPA, 1994). In addition, every state has some recycling and/or waste reduction goal over the next several years ranging from 20 to 70 percent of total waste generated (Steuteville, May 1996: 35).

In order to meet these goals, environmental planners must consider the types of waste generated. In 1994, 38.9 percent of the total MSW generated in the United States was

paper and paperboard products, 28.3 percent was made up of food wastes, yard trimmings, and wood, 7.6 percent was metals, 6.3 percent was glass, and 9.5 percent was plastics (USEPA, 1996: 5). Paper offers the greatest opportunity for an improved waste management policy, as it can be recycled in large quantities (Tchobanoglous, et al., 1993: 49). Yard and food wastes can be composted, which, like recycling, treats and reuses the waste. If necessary, both of these waste streams can also be incinerated. Glass, metals, and plastics can all be recycled to some extent, but care must be taken in the incineration of these as some materials may produce hazardous emissions. The final 9.4 percent of MSW generated in the country consists of materials such as rubber and leather which will not be considered by this research, because each individually makes up a relatively low percentage of the total waste stream.

Environmental planners across the country are faced with the problem of making waste management policy decisions which meet the nation's environmental regulations and goals. Air Force environmental managers are faced with the same problem, how best to manage municipal solid waste while following the guidelines set forth by the EPA and the Air Force.

Previous Work

In 1995, Muratore addressed this same problem -- how best to manage MSW at Department of Defense installations.

In his research he formulated a decision support model intended to produce an optimal policy for an installation's decision maker to adopt in managing the MSW generated at the installation (Muratore, 1995).

In addition, other have expanded upon Muratore's work. Williams developed a model of the recycling process at Air Force installations. His model determines the optimal method by which MSW should be recycled in an effort to minimize cost to the government and maximize the waste diversion from landfills (Williams, 1996). Still considered the social value of various waste management strategies. Her model produces a waste management strategy that maximizes willingness to participate by base workers and residents at Air Force installations (Still, 1996).

Muratore's model was the first attempt at modeling the waste management problem that Air Force decision makers face, but further research has better defined the problem in terms of what decisions can be made at the base level. The current project seeks to provide a more accurate model of the decision process. Where Still focused on the social value of a waste management policy, and Williams dealt solely with the recycling issue in waste management, this research concentrates on developing a decision model that addresses each alternative and objective of waste management and aids the decision maker in selecting the best municipal solid waste management policy for his or her installation.

Research Problem

Almost 800,000 tons of MSW were generated at United States Air Force installations in 1994 (AFCESA, 1996). This research effort examines how to reduce and/or manage that waste while meeting the directives set forth by the Air Force.

Research Goal

The research goal of this study is to develop a decision model that indicates to the decision maker, either the base commander or the base environmental manager, the optimal municipal solid waste management policy for the installation. This optimal policy will be dependent upon:

- the total MSW generated at the Air Force installation being considered,
- the available waste disposal resources,
- the values and preferences of the installation's decision maker,
- any installation-specific constraints that arise, and
- the set of acceptable management strategies.

In determining this optimal policy, the decision model will focus on three objectives derived from Air Force goals (Linthicum and Meinerding, 1997):

- an overall reduction in waste generation rates from a 1992 baseline waste generation weight,
- an increase in waste recycling to 50% of the total waste generated, and

- a waste management policy with a minimal cost (or maximum profit).

Proposed Methodology

In any research effort, it is important to carefully consider the problem. Environmental managers must make a series of decisions in implementing a waste management policy that meets Air Force standards. This research will develop a computer model that reflects those decisions, as well as the many factors that surround those decisions, which will aid the environmental manager in making informed decisions regarding waste management. The model will be developed with the assistance of environmental managers at Wright-Patterson Air Force Base (WPAFB) so that it accurately reflects the nature of the problem.

The first step in this research effort will be to predict the total amount of MSW generated annually at Air Force installations. In doing this, the decision maker can be shown where he or she stands in meeting the stated objective of waste generation reduction. It also allows for a more accurate depiction of the costs involved in the waste management policy. A decision analysis (DA) model will be developed that predicts the total MSW generated at specific installations, dependent upon the number of personnel assigned to and living on that installation.

The DA model will then require a series of inputs from the decision maker that will define the available waste

management resources at or near the installation. The next step will be to model the values and preferences of the decision maker. That will be accomplished by allowing the decision maker to decide which of the stated objectives is the most important goal, if one of the stated objectives is actually a constraint upon the problem, or if the stated objectives should be combined to produce a measure that captures all three goals.

When the assessment of these inputs has been completed, the DA model will then analyze a series of decisions and return an overall score for each waste management policy. The decisions that will be considered by the model include:

- what allocation of funds to motivate source reduction should be adopted by the installation in order to meet reduction goals,
- by which methods should recycling and composting be accomplished at the installation, and

The highest overall value that the model returns for the various waste management policies defines the optimal waste management strategy for the installation under consideration.

A sensitivity analysis of both the input values and the solution will then be conducted. First, the analysis will seek to verify that each input is modeled appropriately, as certain inputs will have a greater impact on the model output than others. Also, the analysis will consider what changes in the overall decision policy might result from changes to the various model parameters.

Finally, validation of the model must be conducted. This will be accomplished primarily by environmental managers at WPAFB. They will carefully review the model to ensure that it accurately represents the problems and the decisions that they are faced with in selecting and implementing a municipal solid waste management policy. Then the model will be run, using WPAFB data, and those results will be reported to the environmental managers along with recommendations concerning the waste management policy.

Chapter II. Literature Review

Overview

This chapter first discusses the waste disposal problem that the nation faces, to include the nature of the problem and the reasons that it exists. Second, it defines the five waste management strategies recommended by the EPA. Third, it describes conflicts that arise when selecting one management strategy over another. Fourth, it outlines some current research efforts in the field of solid waste management and gives a brief description of some of the specific ideas that are being used today to help resolve the waste management problem. Finally, it asks what environmental managers at Air Force installations can do to better manage the waste that is generated there.

Waste Disposal Problem

In 1995, over 300 million tons of municipal solid waste were generated in the United States, all of which had to be disposed in some manner (Steuteville, April 1996: 56). That total does not include the millions of tons of industrial and hazardous waste that were also generated during the same period. While many laws are currently in place to regulate the disposal of this industrial and hazardous waste, the laws that regulate the nation's everyday garbage are generally less stringent.

In 1991, the EPA defined three broad goals for MSW research and development: maximizing the cost-effectiveness of source reduction and recycling, ensuring the safe practice of waste management, and producing innovative technology to deal with increasing levels of MSW (Lewin, 1991: 75). In addition, the EPA in its "Municipal Solid Waste Agenda" (1991) set the priorities of MSW management to be research, reduction, recycling and composting, incineration and landfilling (Lewin, 1991: 75). With these guidelines in mind, it falls to the nation's environmental managers to select the best method for dealing with the waste generated.

Source Reduction

Source reduction is simply a waste management option that reduces the total amount of waste generated that must then be recycled, treated or discarded. How to accomplish this strategy is a much more complex question. While many states have waste reduction goals, it is very difficult to force the public to meet these goals (Steuteville, 1996: 35). For any community to reduce its MSW generated, it would have to rely primarily on the participation of its workers and residents. A reduction in waste can occur only if those people who generate the waste change their habits of use and disposal (Fishbein and Saphire, 1996: 47). While this is unlikely to happen on its own, there are several options to stimulate source reduction as a waste management

strategy. The first of these is regulation. For example, the installation commander could use regulations to amend procurement procedures currently in use, purchasing products that would produce less waste (Freeman, 1989: 13). Another option includes economic incentives or disincentives. Basing waste collection fees on the amount generated in effect rewards people and households that generate less waste, while cash refunds for full recycling bins provide a similar incentive (Freeman, 1989: 15) While economic rewards may not be applicable to military installations, other rewards, such as gift certificates to the Base Exchange, could be used. The final option is education and recognition. As people grow to understand the problem that the nation faces, and the importance of source reduction in alleviating that problem, they will become more likely to participate in waste reduction programs (Freeman, 1989: 19-20).

Composting

Composting is a specialized form of recycling, in that it is the recycling of organic materials. Specifically, materials conducive to composting include yard wastes such as grass trimmings and leaves, food wastes including table scraps and fruit peels, non-recyclable paper such as used paper towels and napkins, and pet waste ("Composting", 1992: 74). In fact, compostable material is estimated to make up

about 50 percent of the MSW generated in United States ("Composting", 1992: 72).

As with source reduction, composting requires a commitment by the individual. It means the use of a separate bin or bag to collect compostable materials versus other waste, and someplace to actually compost the material, whether it be by the individual in the backyard or through a collection service and a central location ("Composting, 1992: 72).

Recycling

Recycling is perhaps the best known waste management strategy, as it has been heavily promoted over the past few years. It is not, however, the complete solution to the waste dilemma many people believe. In fact, there are several problems with recycling efforts. First, there is a shortage of markets, either due to lack of interest or lack of education. Second, there is a shortage of processing facilities across the country. And third, recycling programs are costly to start and operate (Fishbein and Saphire, 1992: 47). Indeed, the cost of recycling materials is generally greater than the revenues gained from recycling those materials, but that cost is often outweighed by environmental concerns (DeLong, 1994: 37).

Despite these problems, there is a great deal of room for the improvement of waste management through the use of recycling. It is estimated that the total MSW landfilled in

the country could be reduced to 10 to 15 percent of its current level if everything possible were recycled (DeLong, 1994: 37). While 85 to 90 percent recycling may not be a realistic goal, there is clearly an opportunity to improve from the 27 percent of MSW that was recycled and composted in 1995 (Steuteville, 1996: 54). In fact, Japan as a whole recycled 50 percent of its total MSW in 1990 (Liptak, 1991: 87). J. Winston Porter, former EPA assistant administrator, disagrees about potential recycling and instead believes that 30 percent recycling is the upper limit for the country ("US Recycling", 1996: 14), while William Franklin of Franklin Associates, the company that conducts much of the EPA's research, reports that levels of 40 percent can be achieved, particularly at the community level ("US Recycling", 1996: 14).

Incineration

Incineration, or waste combustion, is the burning of waste. Depending on the type and quality of incinerator used, the process reduces the amount of waste to be landfilled to between 10 and 30 percent of its original weight (Liptak, 1991: 95, 287). Incineration can also result in the generation of electric power or heat (Liptak, 1991: 95). Despite these benefits, incineration is perhaps the most controversial of the five waste management strategies, and it is also the most strictly regulated. Although 95 percent of all harmful dioxins in the atmosphere has been

attributed to waste combustion (Johnson, 1995: 33A), an average individual's exposure to these dioxins is no more harmful than his or her exposure to secondhand cigarette smoke (Rogers, 1995: 14).

Because of the public's fear of health risks associated with the operation of incinerators, the EPA is creating new regulations that will reduce incinerator emissions 99 percent (Johnson, 1995: 33A). The use of new technology, such as air scrubbers, baghouses, and the injection of activated carbon (Johnson, 1995: 34A), in conjunction with regulatory reviews of trial burn data that estimate the risk to public health of incinerator emissions (Rogers, 1995: 13), should quell the public fear of incinerators. Today, the risk of contracting cancer as a result of incinerator emissions is well below the EPA standard of one excess death per one million people exposed (Rogers, 1995: 14).

Landfilling

Landfilling, the last resort strategy, is currently the most common method of waste disposal in the United States. In 1995, 63 percent of the total MSW generated, over 200 million tons, was landfilled (Steuteville, 1996: 56). Landfilling is still a relatively inexpensive disposal method, ranging from 100 dollars per ton for smaller landfills to less than 50 dollars per ton for larger facilities (DeLong, 1994: 36). However, the cost of landfilling is increasing due to stiffer EPA regulations

governing landfill locations and emissions (Arrandale, 1995: 69). Also, tipping fees, or the cost of depositing waste in a landfill, are on the rise. This is particularly evident in more populated areas, where more waste is generated and more landfilling is required (Arrandale, 1995: 70).

Many environmentalists who argue for increased reduction and recycling of MSW cite the notion that the nation is running out of space to use as landfills. Others argue, however, that the nation is running out of space that the public would be willing accept as landfill sites (DeLong, 1994: 35). In fact, if landfilling is done properly, which is much more likely with today's tight restrictions and strict regulations, there is enough available land area in the country to continue to landfill for millions of years (DeLong, 1994: 35). The problem stems from the public's "not-in-my-backyard" opinion. The public's acceptance of landfills might increase through education as to the current safe practices of landfilling, as well as their potential of being made into parks, golf courses, ski resorts, etc., when they are full (DeLong, 1994: 39).

Conflicting Interests

The problem in adopting a "good" waste management policy lies in the inherent conflicts between the potential strategies. The current standards in the United States

recommend recycling and composting, and then using small-scale incineration to divert as much waste as possible from landfills (Grogan, 1996: 86). Selecting one strategy to the exclusion of others, however, sometimes leads to conflict between and within the industries that accomplish the waste management.

The greatest conflict arises from the costs associated with each method. Landfills are significantly cheaper to build and operate than incinerators, and therefore the waste disposal cost to either the government or the consumer is higher if the current hierarchy which places incineration ahead of landfilling is used (Arrandale, 1995: 70-72). Also, if the higher-cost incinerator is built, fewer funds will be available to expand the more desirable recycling option (Arrandale, 1995: 74). Another consideration is the competition between incineration and recycling or composting due to planning commitments, as only so much land may be used for the facilities necessary to accomplish these strategies (Grogan, 1996: 86). Also, many recyclable materials may be lost through incineration (Grogan, 1996: 86), but increased recycling leads to a decline in the cost effectiveness of incinerators (Arrandale, 1993: 56).

Current Practices

Waste management is a problem that has been addressed for many years, yet the problem remains. People find it

easier to throw their waste in the trash rather than find a way to reuse, recycle, or compost it (Dinan, May/June 1992: 13). Even so, the relative reliance on landfills is declining. The EPA predicts that the waste recovery rate in the country will rise to 30 percent by the year 2000, and the amount of landfilled waste will fall to 55 percent in the same time ("EPA Predicts Drop", 1995: 6).

Today, there are many projects underway and planned which target the problem of waste management. The EPA and Procter & Gamble recently began a joint research project concerning the composting process ("Optimal Composting Conditions", 1996: 8). Researchers at the Massachusetts Institute of Technology's Plasma Fusion Center have developed a furnace that vitrifies waste, but produces fewer gaseous emissions than incineration and leaves blocks of glass rather than traditional ash as its residue (Peterson, 1995: 282).

In addition to these large projects, there are many smaller scale practices being used throughout the country. Waste assessments are used to target source reduction and recycling opportunities for businesses (Cate, 1995: 23). Material exchange programs are in use in many small business communities, and could be implemented at Air Force installations, while unit pricing for waste collection and backyard composting projects are in practice in many residential communities (Cate, 1995: 23-24). Even large

companies are doing their part. AT&T has replaced its traditional copy machines with two-sided copiers, and several grocery store chains, to include Giant Food, offer consumers rebates for returning grocery bags (Mamis, 1993: 48).

Decision Analysis

One method for approaching the waste management problem involves the use of decision analysis. Decision analysis is a structured, iterative process in which the analyst and decision maker identify the problem to be addressed, as well as the objectives and alternatives that help define the problem. Then through careful modeling and repeated consultations with the decision maker to adapt to any changes in the problem structure or surrounding issues, the analyst can show the decision maker which alternative provides the best solution to the problem. Decision analysis allows the analyst to model many decisions, alternatives, and objectives, as well as known values and uncertain events (Clemen, 1991). A more detailed discussion of decision analysis can be found in Appendix A.

Chapter III. Methodology

Decision Analysis

Decision analysis is a useful tool for modeling complex problems in which there are several sequential and/or dependent decisions to be made. It allows the analyst to model these decisions and their associated alternatives, as well as any other events, deterministic or uncertain, that define the problem. For an environmental manager at a specific Air Force installation to select the best waste management policy, many questions must be answered. He or she must consider the facilities, services, and markets available locally, the personnel assigned to the installation, and the types and amounts of waste generated at the installation. Because of the complexity of this problem, including several decisions, such as waste reduction strategies and waste collection programs, that must be made by the environmental manager, the waste management problem is well-suited to decision analysis. A decision analysis model will include installation-specific restrictions, requirements, and data to assist the decision maker in selecting the best waste management policy for the installation. Therefore, this chapter models the problem of installation-level MSW management using decision analysis.

Modeling the Problem

The first step in modeling the waste management problem is to accurately define the problem. For the environmental manager, the overriding question that must be answered is: "how to reduce the waste generated at the installation, and how to best dispose of the waste that is generated so as to meet Air Force and installation requirements?" In answering these questions, there are several key factors that must be considered. First, the model objective or objectives must be established. Next, the decision maker must define what facilities are available for use by the installation, what operational alternatives are feasible, and what disposal options are acceptable. Finally, any uncertainties and values that are relevant to the problem must be modeled.

Objectives

For many Air Force problems, the objectives are often set by someone much higher than the decision maker. The waste management problem is no exception. The Air Force has dictated the following waste management objectives for all bases (Linthicum and Meinerding, 1997):

- achieve a 50 percent reduction by weight, from a 1992 baseline, in total waste generated by 1999,
- achieve 50 percent recycling of that waste generated, and
- minimize the cost of the selected programs.

Decisions

In modeling this problem, it is important to consider what facilities are available for the installation's use in its waste management policy. Because landfilling and recycling have been in practice at Air Force installations worldwide for many years, it can be assumed that facilities for those two waste management strategies will be available for the base's use. Therefore the other two waste management facilities, compost facilities and incinerators, must be considered. The analyst must determine whether or not there is a compost facility or an incinerator available locally, and if it is operated by the Air Force or if its use must be contracted. This determination has a controlling influence on the modeling effort.

Another determination that should be modeled is the type of waste disposal regulations that are in place at the installation. If there are recycling and/or composting requirements, then the model may recommend a different policy than if those regulations were not in place.

The decisions that the environmental manager are then faced with include:

- which waste collection methods should be used for delivery to recycling facilities,
- which waste collection methods should be used for delivery to composting facilities, and
- whether or not waste collected for landfill disposal should first be treated at an incinerator.

It is important to distinguish between collection methods for the residential and commercial sectors of the base. For this model, the residential area of the base is limited to military family housing, and the commercial area of the base includes offices, shops, MWR and AAFES facilities, etc. Because different waste is generated in residences than in offices, and because residential waste is often collected separately from commercial waste, it is necessary to consider different collection methods for the two areas.

There are four decisions that must be modeled with regard to collection methods. Those decisions are: (1) Commercial Recycling Collection Method; (2) Residential Recycling Collection Method; (3) Commercial Composting Collection Method; and (4) Residential Composting Collection Method. For decisions (1) and (2), the available alternatives are: (a) a central drop-off location; (b) several satellite drop-off locations; (c) a commingled curbside or office collection; or (d) a source separated curbside or office collection. For decisions (3) and (4), the available alternatives are: (a) a central drop-off location; (b) several satellite drop-off locations; (c) curbside or office collection; or (d) no collection (if there is no facility available).

Another question that must be answered is whether or not to incinerate waste, if their is a waste combustion

facility available for the base's use. If such a facility does exist, then the decision maker must decide if the waste collected on the base for delivery to a landfill should first be treated at the incinerator.

A final issue that must be considered is how best to reduce the amount of waste generated at the base. That is, in what area should the base environmental office focus its efforts and resources in an attempt to reduce the amount of waste generated. The infinite number of possibilities have been categorized into five alternatives. First, take no action to reduce the waste generated. Second, purchase more equipment that may facilitate source reduction, such as two-sided copiers. Third, regulate the commercial area of the base, (e.g. require the use of electronic mail rather than paper copies). Fourth, focus on educating the base personnel and residents as to their role in the environment, encouraging individuals to reduce the amount of waste they generate. Finally, use a combination of these strategies to reduce waste.

In review, the model includes six decisions that the environmental manager must make in selecting a waste management policy. They are:

1. Commercial Recycling Collection Method (CRCM)
2. Residential Recycling Collection Method (RRCM)
3. Commercial Composting Collection Method (CCCM)
4. Residential Composting Collection Method (RCCM)
5. Waste Incineration (WI)
6. Source Reduction Methods (SRM)

The set of feasible alternatives for each of these decisions is redefined in Table 1. It is important to note, however, that the waste incineration decision for Wright-Patterson AFB must be controlled to **No**, as the base cannot incinerate its municipal solid waste due to the imminent closure of the local facility (Linthicum and Meinerding, 1997).

Table 1. Strategy Generation Table

CRCM	RRCM	CCCM	RCCM	WI	SRM
Central	Central	Central	Central	Yes	None
Satellite	Satellite	Satellite	Satellite	**No**	Equipment
Commingled	Commingled	Pickup	Pickup		Regulation
Separated	Separated	None	None		Education
					Combination

Uncertainties

When the decisions, alternatives, and controls that are relevant to the problem have been enumerated and modeled, then the analyst and decision maker must consider what uncertain events might influence the outcome of the decision policy. A deterministic analysis of the problem, discussed in Chapter 4, show which variables should be modeled as uncertainties.

One principal uncertainty is the participation of the base personnel and residents in the various recycling programs. The base can have the best possible waste management plan, but if the people do not participate the goals will not be met.

As with the decisions discussed above, it is equally important to differentiate between base workers and residents when modeling participation rates, as individual attitudes towards recycling vary from home to the workplace (Still, 1996). Therefore the waste management model includes two uncertain events, or uncertainty nodes, that reflect recycling participation rates: (1) Commercial Recycling Participation; and (2) Residential Recycling Participation.

The participation rates used in this model are approximated using a beta distribution. While it is difficult to predict actual participation rates, average participation in various programs is widely accepted. And

because the low and high participation rates can be fixed at 0 and 1, respectively, the beta distribution can provide a picture of true participation using the average and maximum variance. This allows for random selection of the participation rates actually used in model calculations, because these rates are not constant, while at the same time keeping the rates close to the average value. A more detailed explanation of how the beta distribution was applied to the participation rates can be found in Appendix B.

Table 2 shows the average recycling and composting participation rates used in the model based on various programs currently in practice across the country (Oskamp, et al., 1996: 80), separated by the area of the installation as well as by the collection alternatives. (The composting participation rates are not modeled as uncertainties -- their average values are used in the model. The reasons for this will be explained in the following chapter.) The values in the table are also dependent upon the assumption that no regulations are in place at the installation regarding participation in either of these programs. Because participation in a recycling or composting program is an individual decision, it is also assumed that residential participation rates will be slightly higher, about 5 percent on average, than commercial rates due to the family structure. This 5 percent difference was suggested

by the environmental manager and is a default value that can be adjusted if necessary. A final assumption is that as the level of convenience to the individual increases, so too will the level of participation (Still, 1996).

Table 2. Recycling and Composting Participation Rates, without Regulations

Collection Method	Recycling Commercial	Recycling Residential	Composting Commercial	Composting Residential
Central	0.22	0.27	0.10	0.15
Satellite	0.32	0.37	0.20	0.25
Commingled	0.53	0.58	0.35	0.40
Separated	0.37	0.42	---	---

For the case when regulations are in place on the installations, many of the same assumptions hold true. One major difference, however, lies in the assumption that residential participation rates are slightly higher. In the case of regulated participation, particularly on a military installation, individuals in the commercial sector are more apt to comply with those regulations than individuals in residential areas. This is due to the increased visibility of their actions, thereby making the regulations easier to enforce. Therefore it is assumed that commercial participation rates will be somewhat higher, again about 5 percent on average, than residential participation rates in this case. It is also assumed that the average commercial participation rates will increase 25 percent with the

implementation of regulations. These values are not supported by the literature, but are used to indicate the approximate magnitude of the difference and to illustrate the flexibility of the model. Again, these percent differences were suggested and can be adjusted by the decision maker to reflect his or her experience concerning participation rates. The average participation rates in recycling and composting programs when regulations do exist are shown in Table 3, based on the rates reported in Table 2, the stated assumptions, and programs currently in practice such as the East Hampton, New York composting project ("Good Response…", 1995: 25).

Table 3. Recycling and Composting Participation Rates, with Regulations

	Recycling		Composting	
Collection Method	Commercial	Residential	Commercial	Residential
Central	0.47	0.42	0.35	0.30
Satellite	0.57	0.52	0.45	0.40
Commingled	0.78	0.73	0.60	0.55
Separated	0.62	0.57	---	---

Another key uncertainty to the waste management problem is the revenue that is obtained from selling recyclable materials. Because of the types of materials that can be recycled, and the fluctuating supply and demand of those materials, it is unwise to model the revenue from recyclable material sales as a fixed price. Instead it should be

modeled as a random variable. The sale of recyclable materials at Wright-Patterson Air Force Base in 1996 yielded overall revenues of $50 per ton. Based on this number as well as ranges supplied by the decision maker, the Recycled Materials Price uncertainty is modeled as a normal distribution with a mean of 50 and a standard deviation of 15. The mean value is based on the historical sales prices at WPAFB. The standard deviation is based on the knowledge that the sale price of materials cannot drop below zero, and a variation of three standard deviations from the mean encompasses 99 percent of all possible values. The selection of 15 allows for the slight probability that sale prices will drop nearly to zero or nearly double, but will generally remain near the mean. While different materials do yield different recycling revenues, this distribution considers the prices and amounts of all recyclable materials, and the changes in overall revenues from all recyclable materials.

The final uncertainties that are important to the waste management problem relate to the source reduction methods. First, dependent upon the available funds, the base can spend a wide range of money on the implementation of education programs, implementation and enforcement of regulations, and/or the purchase of new equipment to facilitate source reduction. The low amount on this range will always be set at $0, as the decision maker does not

have to direct any money towards waste reduction. The high amount, however, is dependent upon both the importance of waste reduction to the decision maker as well as budgetary constraints. For Wright-Patterson Air Force Base, that high amount has been set at $200,000 by the environmental managers.

Also, individual participation in source reduction is uncertain. This is reflected in the waste generation level that is achieved under various source reduction programs. Depending on where the base focuses its attention with respect to source reduction, the individual may be more likely to reduce the waste that he or she generates. This participation is also modeled using a beta distribution, after adjusting to a 0 to 1 range. Instead, the possible range of waste generation rates must be considered. The high waste generation rate is approximately 4.4 pounds per person per day (PPD), or .80 tons per person per year (TPY). The absolute low value is about 2.75 PPD, or .50 TPY. These high and low values reflect, respectively, the national average waste generation rate and the absolute lowest waste generation rate that the environmental managers at Wright-Patterson AFB believe can be achieved. Normalizing these values (.80, .50) to a zero-one scale, the expected waste generation rates under various source reduction programs can be predicted and used in the beta distribution as participation rates. Table 4 shows the expected waste

generation rates in pounds per person per day (PPD) and tons per person per year (TPY) for the various source reduction methods, and the normalized average value used for the beta distribution in the model. The values in the table are the decision makers' best guess concerning the waste generation rates that would be achieved under the various source reduction methods.

Table 4. Waste Generation Participation Rates

	Source Reduction Method				
	None	Equipment	Regulation	Education	Combination
PPD	4.00	3.67	3.50	3.33	3.00
TPY	.73	.67	.64	.61	.55
Normalized Average	.767	.567	.467	.367	.167

In review, the variables in this problem that are modeled as uncertainties are:

1. Commercial Recycling Participation Rates
2. Residential Recycling Participation Rates
3. Recycled Materials Sales Revenue
4. Source Reduction Costs
5. Waste Generation Rates

Values

In accurately modeling the waste management problem, it is necessary to properly model various numerical values, both input and output.

The input values used in the problem are the base population and the 1992 baseline value for waste generated. These amounts are known by the decision maker and are vital in measuring whether or not objectives are met.

There are also many intermediate values which must be calculated before the outcome values can be used to determine the optimal decision policy. The first of these is the total waste generated (Appendix B, Equation 1). This amount is dependent upon both the base population and the waste generation rate for the source reduction method that is selected. From this, the waste generated in the commercial and residential areas of the base is calculated (Equations 2 and 3). These amounts in turn influence the levels of commercial and residential waste that are recycled and composted (Equations 4 through 7). From these amounts, the cost of operating the various collection and disposal programs is calculated (Equations 8 and 9).

Once these calculations have been made, the model then generates a final output based upon the objectives of the decision problem: 50 percent source reduction, 50 percent recycling, and minimum cost. The environmental managers at WPAFB have weighted the relative importance of each of these objectives, with the source reduction goal at 30 percent of the total, the recycling goal at 60 percent, and the cost goal at 10 percent. These weights were determined in two ways. First, the decision makers directly compared the

objectives, indicating that waste reduction is three times as important as profit/cost and that recycling level is twice as important as waste reduction. Then they also placed values between one and ten on each objective, summing those values to 10. The two methods were consistent with each other, therefore defining the appropriate objective weights. The final output that is generated using these weights is the measure by which the various alternatives are compared, with the highest score reflecting the best policy.

The Model

Using the information described in the previous sections, as well as in Appendix A, a decision model was constructed using the DPL™ Programming Language (DPL™, 1995).

After determining which decisions, uncertainties, values and objectives make up the model, the next step is to decide what influences exist between the various parts of the problem. In accomplishing this, the first step is to visually depict which decisions must be made and the objective(s) or outputs that are defined by those decisions. Figure 1 shows an initial influence diagram which illustrates the problem decisions and objectives, as well as the influences that exist between them.

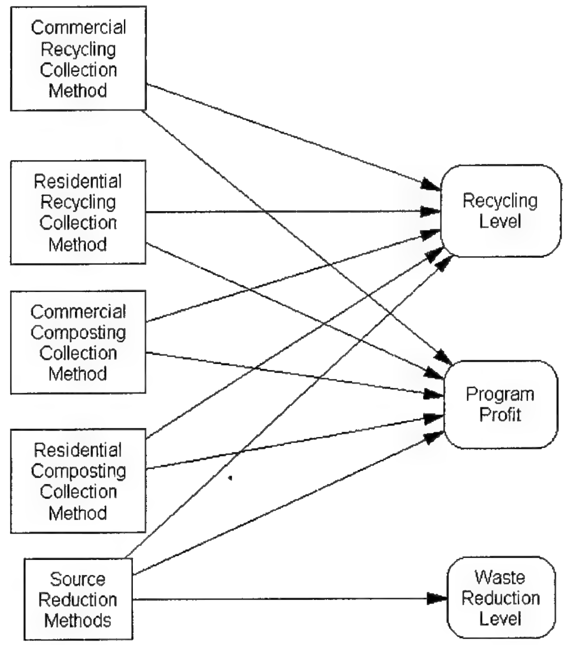

Figure 1. Waste Management Model, Decisions and Objectives

Having developed a general model of the decision problem, it is then necessary to model the influence of the uncertainty and value nodes. It is important to recognize that the decisions themselves are not the only influencing factors on the final objectives. In fact, often the decisions have only an indirect influence on these objectives. It is the intermediate value and uncertainty nodes which have direct influences on the outputs. Figures 2 through 4 depict the decisions and related uncertainty and value nodes that make up the recycling, composting, and waste reduction portions, respectively, of the overall decision model, as well as the influences on the objectives.

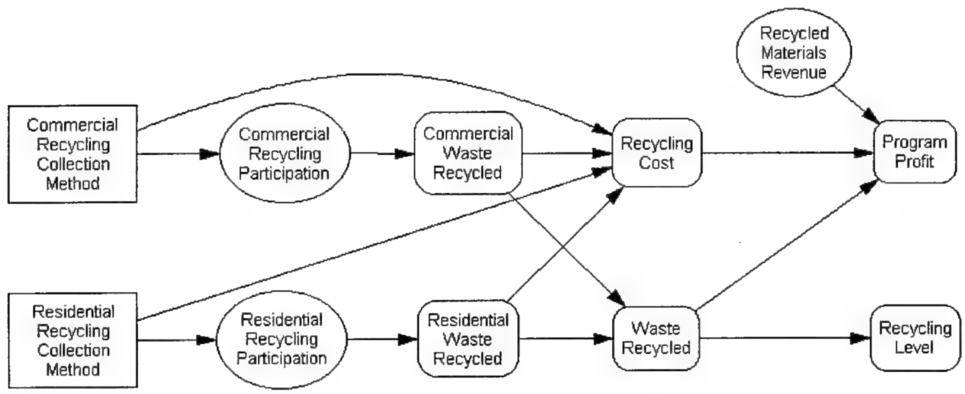

Figure 2. Waste Management Model, Recycling Decisions and Influences

The recycling decisions and associated uncertainties and values are depicted, as well as the existing influences, in Figure 2. The two decisions have a direct impact on both the respective participation rates, as participation rates are dependent upon which collection method is used, as well as the recycling cost, because different collection methods incur varying costs. Also, the participation rates directly affect the amount of waste recycled in each area, as higher recycling levels will result from higher participation rates. The recycling cost is a function of both the collection method and the amount of waste recycled. Finally, both the costs associated with recycling materials

and the revenues obtained from selling recyclable materials influence the profit of the selected recycling program, and the total amount of waste recycled is used to determine the level of recycling that the base reaches.

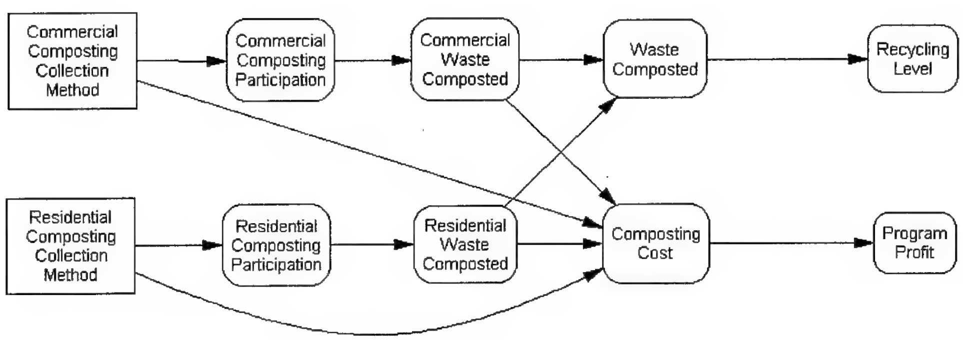

Figure 3. Waste Management Model, Composting Decisions and Influences

The composting portion of the model, depicted in Figure 3, is very similar to the recycling portion shown in Figure 2. It carries many of the same influencing factors. The decisions again directly affect the participation rates and overall composting costs, and the participation rates in turn determine the amount of waste that is composted. Also, the waste composted and the collection methods again

determine the total cost associated with composting. The primary difference in the two portions lies in the influences on the program profit. Materials that are collected as compost are not sold for revenue, so only the compost cost affects the profit, but the amount composted does affect the recycling level that the base can achieve.

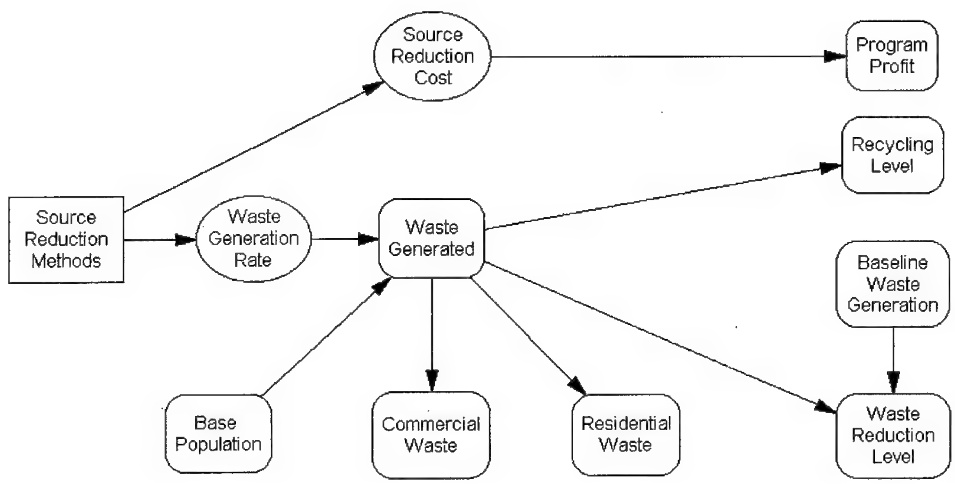

Figure 4. Waste Management Model, Source Reduction Decisions and Influences

The source reduction portion of the model is shown in Figure 4. Both the cost of implementing source reduction programs and the waste generation rate that is realized on base are directly impacted by the source reduction method that is selected. A more complex program will require greater funding, but will result in reduced waste

generation. The waste generation rate, when multiplied by the base population, results in the actual amount of waste generated on the base. That amount in turn determines the amount of commercial and residential waste that is generated. All three objectives are also affected in this portion of the model. The program profit is influenced by the cost of the source reduction method that is selected. The recycling level is a function of the amount of waste generated. And the waste generation level is measured by forming a ratio of the waste generated under the selected program to the baseline waste generation amount of 17,000 tons per year.

A final step that is required before the model can be completed is to determine how to combine the three objectives so that each is considered when selecting the decision policy. Because the problem has three conflicting objectives, with two different measures, multi-attribute utility theory should be used to form a single measure to compare alternatives. The decision makers at WPAFB have weighted the three objectives -- waste reduction, recycling level, and cost -- at 30 percent, 60 percent, and 10 percent, respectively, using the methodology previously discussed. The decision makers also indicated that each of the three objectives has no impact on the two remaining objectives. For example, the decision makers would assess the same certainty equivalent to a specific program profit

regardless of what recycling and reduction levels are reached. That is, the same program cost would receive the same level of utility regardless of the recycling or waste reduction level. Therefore, it is assumed that the three objectives exhibit utility independence. Further, the decision makers also agreed that if there were chance (or lotteries) associated with each of the attributes, a change in the lottery of one of the attributes would not influence their preferences regarding the lotteries of the other attributes. Therefore, the three objectives also exhibit additive independence, and so a simple additive multiattribute utility function can be used to combine the three objectives (Clemen, 1991: 478-483). Having determined the relative weights of each objective, and having established utility independence, it is necessary to develop utility functions that accurately measure the value of each objective on a common scale, with utility values ranging from 0 to 1 (Clemen, 1991: 445).

In building these utility functions, it is imperative that the decision makers' preferences and inputs be carefully evaluated. For this decision problem, the decision makers themselves aided in the development of the graphical depiction of the utility functions, which in turn have been converted into mathematical equations for use in the model.

The utility functions for the first two objectives, waste reduction and recycling level, are shown to have an exponential increase in utility, from 0 to 1, as the level of reduction or recycling increases from 0 to 50 percent. Any level greater than 50 percent results in a utility value of 1. This indicates that the decision maker is interested only in meeting the stated goals of the Air Force, that any recycling or waste reduction level greater than 50 percent, be it 51 percent or 99 percent, is equally good. Figures 5 and 6 show the utility functions that have been developed for the waste reduction and recycling objectives. Equations 13 and 14 in Appendix B show the mathematical interpretation of these graphs.

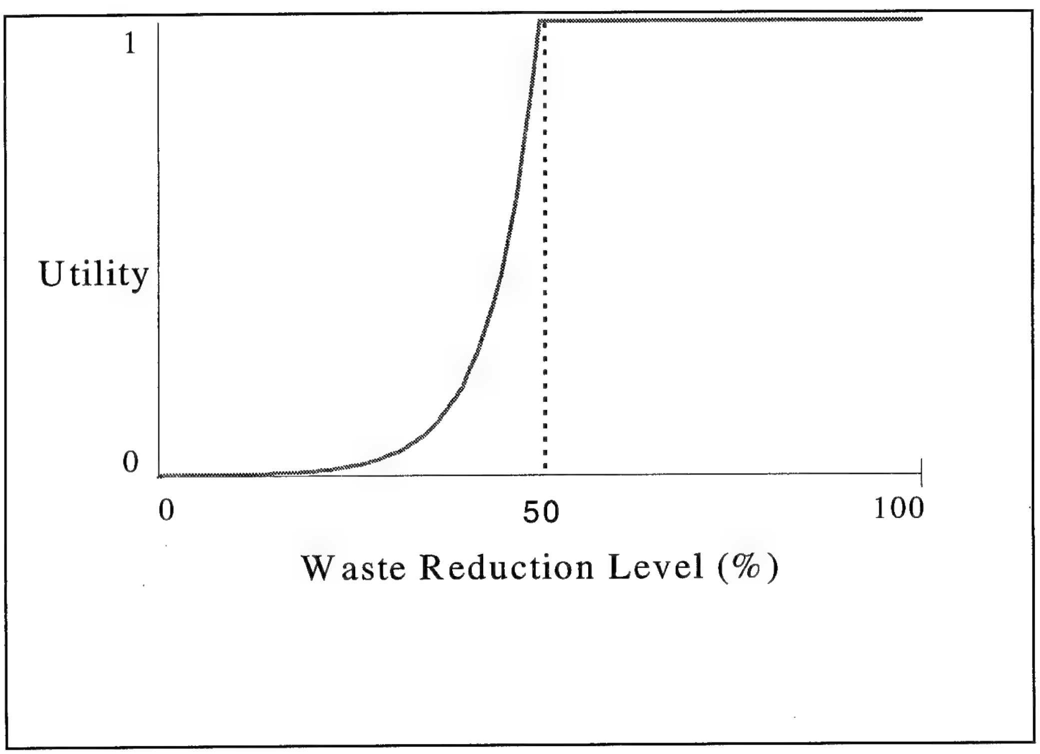

Figure 5. Utility Curve, Waste Reduction Level

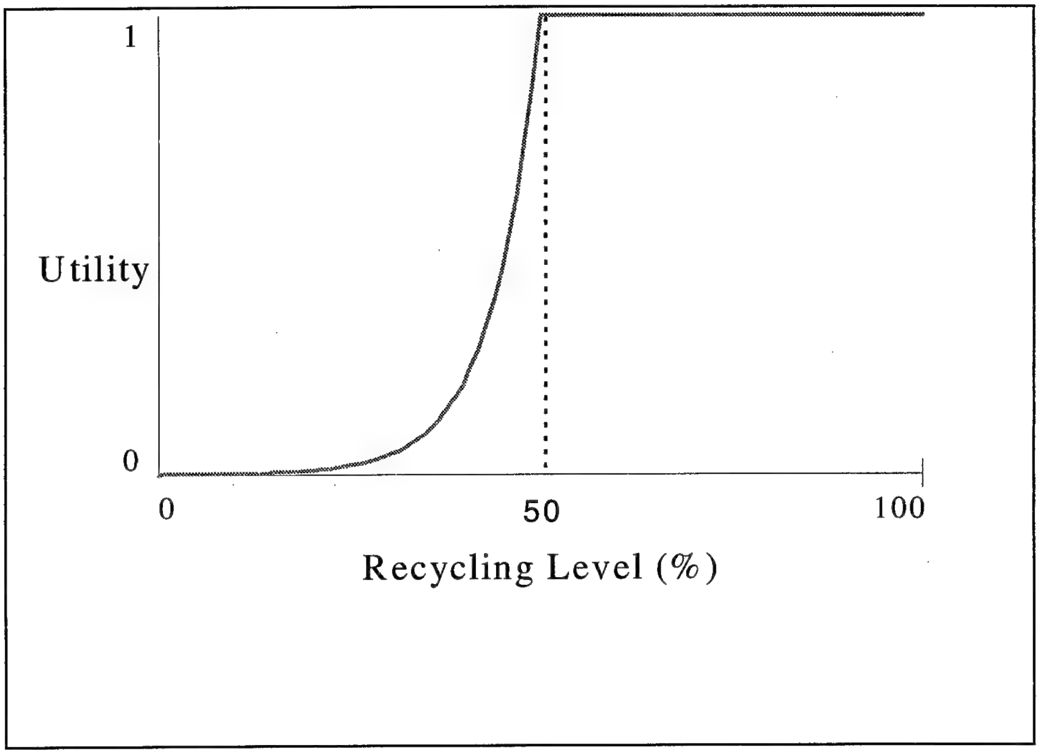

Figure 6. Utility Curve, Recycling Level

The utility function for the cost objective is a simple linear function. The worst case scenario for any possible decision policy is a cost of $420,000 annually. The best case scenario is an annual cost of only $100,000. These values were obtained by simply running the model to maximize and minimize the profit, respectively. Therefore, the utility values for the cost objective range from 0 at a $420,000 cost to 1 at a $100,000 cost, which is depicted in Figure 7. Equation 15 in Appendix B defines this utility function.

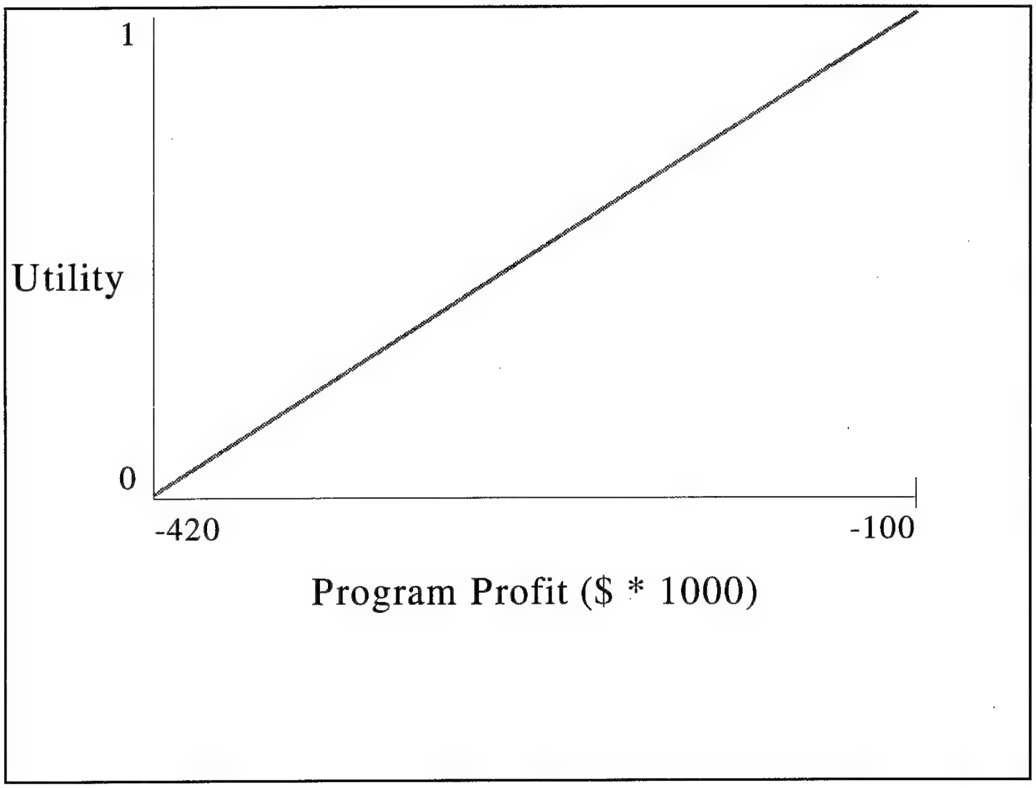

Figure 7. Utility Curve, Program Profit

Once these utility functions have been developed, the three objectives may be combined using the utility functions and weights to produce a single output that measures the overall value of a decision policy.

The final step is to put the different pieces of the model together. By combining the influence diagrams pictured in Figures 1 through 4, and by using the equations listed in Appendix B, the model as depicted in Figure 8 was developed.

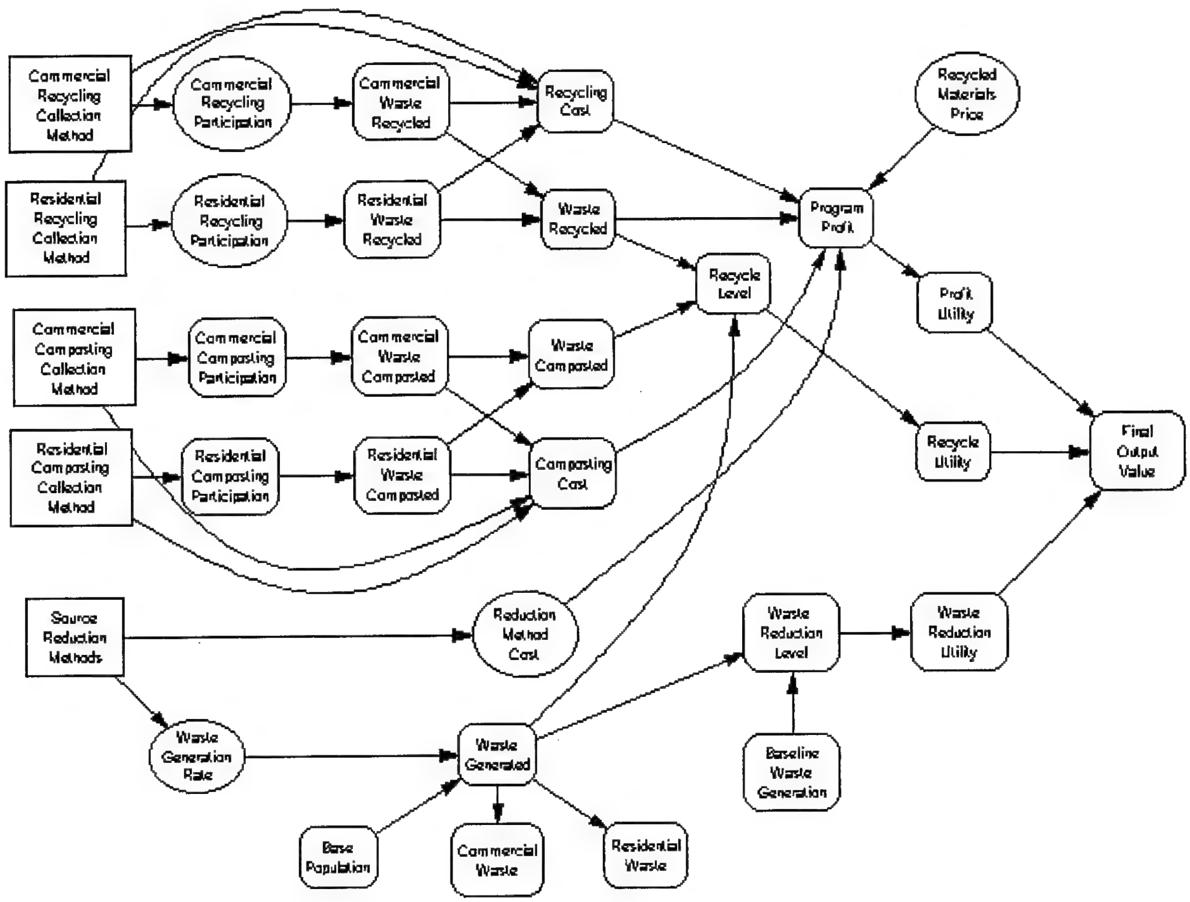

Figure 8. Waste Management Model Influence Diagram

This figure also depicts the influences that connect the portions of the model shown in Figures 2 through 4. Those figures indicated the influences that each portion of the model had on the three objectives. This figure shows how the different portions are related by their respective influences on those objectives. It also shows how the three objectives are combined into a single score. The values for Waste Reduction Level, Recycle Level, and Program Profit are defined by Equations 10 through 12 in Appendix B. These raw values are converted to utility values using the utility

functions depicted in Figures 5 through 7 (Equations 13 through 15). Finally, the utility values are combined using the following equation (also found in Appendix B) to produce an overall score for each possible decision policy.

$$\textbf{Final Output Value} = (\,0.3 * \textbf{Waste Reduction Utility}\,) + (\,0.6 * \textbf{Recycle Level Utility}\,) + (\,0.1 * \textbf{Profit Utility}\,) \qquad \textbf{(16)}$$

Using this model, a waste management decision policy which meets the stated objectives of the Air Force will be recommended. That recommended decision policy and the associated output values will be discussed in the subsequent chapter.

Chapter IV. Analysis and Findings

Introduction

The decision analysis model developed in this research effort has been designed to provide the environmental managers at WPAFB a tool with which the base's optimal waste management policy can be selected. Each potential decision policy is scored in three categories -- waste reduction, recycling level, and cost -- and these scores are then combined to produce an overall score for the decision policy. The highest overall score defines the recommended waste management policy for WPAFB.

Using data obtained from WPAFB, a complete analysis of the problem was conducted. First, an initial decision analysis was performed, followed by a value sensitivity comparison to identify the variables with the greatest effect on the solution. These variables were then modeled as uncertainties and decision analysis was conducted on the revised model to obtain the final solution.

Initial Analysis

The initial analysis was conducted using a model in which all uncertainties were converted to expected values. The initial analysis resulted in the following optimal waste management policy, which produced an overall score of 0.699: commingled curbside collection of recyclable materials in the commercial areas of base and central collection of

recyclable materials in the residential areas of the base, no compostable materials collection in either area of the base, and no source reduction methods. The overall score reflects a policy that yields an expected recycling level of 50.7 percent of all waste generated annually, a waste reduction level of only 9.8 percent from the baseline amount, and a program cost of approximately $103,000 per year. This decision policy is reflected in Figure 9. The bold lines indicate which alternative for each decision is selected in the optimal policy, and the final number is the overall score that this decision policy receives.

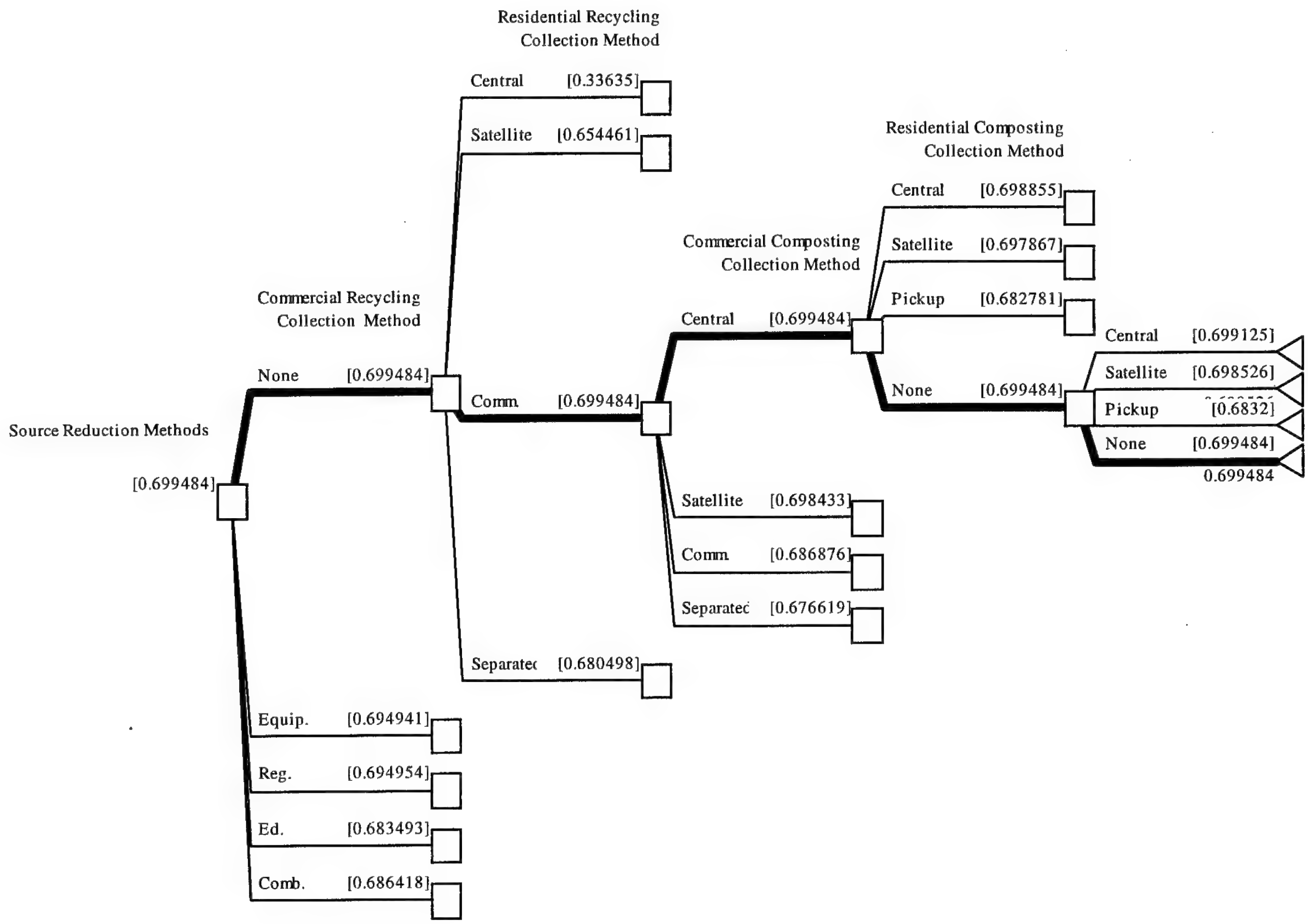

Figure 9. Optimal Decision Policy Without Uncertain Events

Sensitivity Analysis

A value sensitivity comparison of the fixed values in this model shows which variables are most influential upon the outcome, and should therefore be investigated further. Figure 10 shows a tornado diagram of these variables, which graphically depicts the relative influence of each variable on the final outcome of the model.

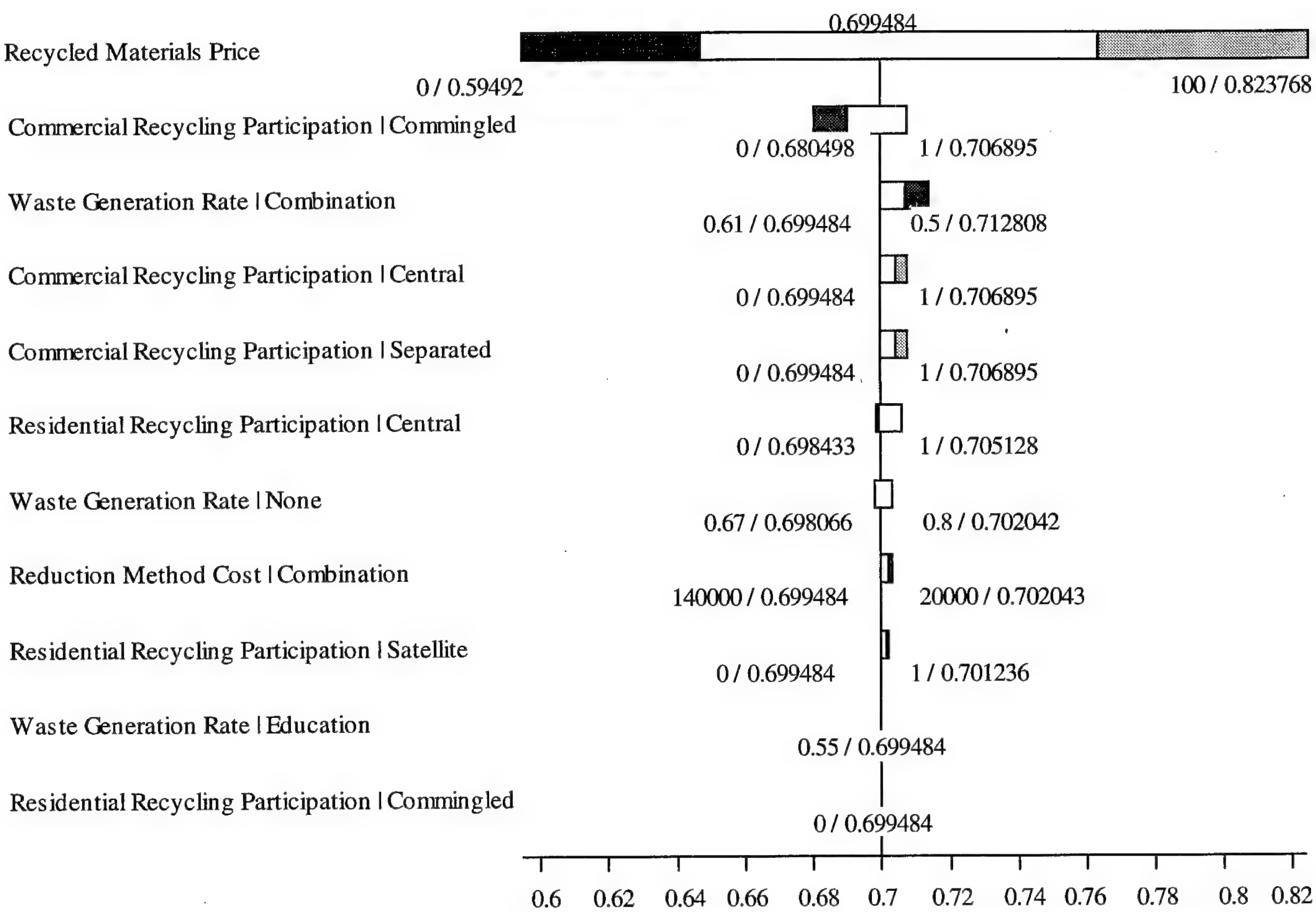

Figure 10. Value Sensitivity Comparison

While the graph depicts only eleven of the twenty-five variables that were considered, it does indicate that only the first nine variables listed have an impact on the outcome of the problem, shown by the width of the bars. Variation in any of the other variables has no impact on the overall score of the selected decision policy. In addition, seven of those nine variables show a color change somewhere on the bar that indicates a decision policy change would occur if the variables were adjusted towards either their high or low values. These variables were further analyzed using rainbow diagrams to determine at what level the change in the decision policy would occur.

The significance of Figure 10 is that it shows that the variables "Waste Generation Rate", "Recycled Material Price", "Reduction Method Cost", "Commercial Recycling Participation", and "Residential Recycling Participation" should all be modeled with uncertainty, because the natures of these variables indicate that they represent uncertain events and variability in their values results in different model results. Also note that the value sensitivity comparison does not indicate that it is necessary to further investigate the composting participation rates, either commercial or residential, as changes in those variables have no impact on the outcome of the decision model. Therefore, these two variables are modeled as simple value

nodes using only the average participation rates for each collection method.

The rainbow diagrams for two of the variables shown in Figure 10 to warrant additional analysis, recycled materials price and commingled commercial recycling participation, are shown in Figures 11 and 12 as examples to further illustrate the importance of modeling these variables as uncertainties.

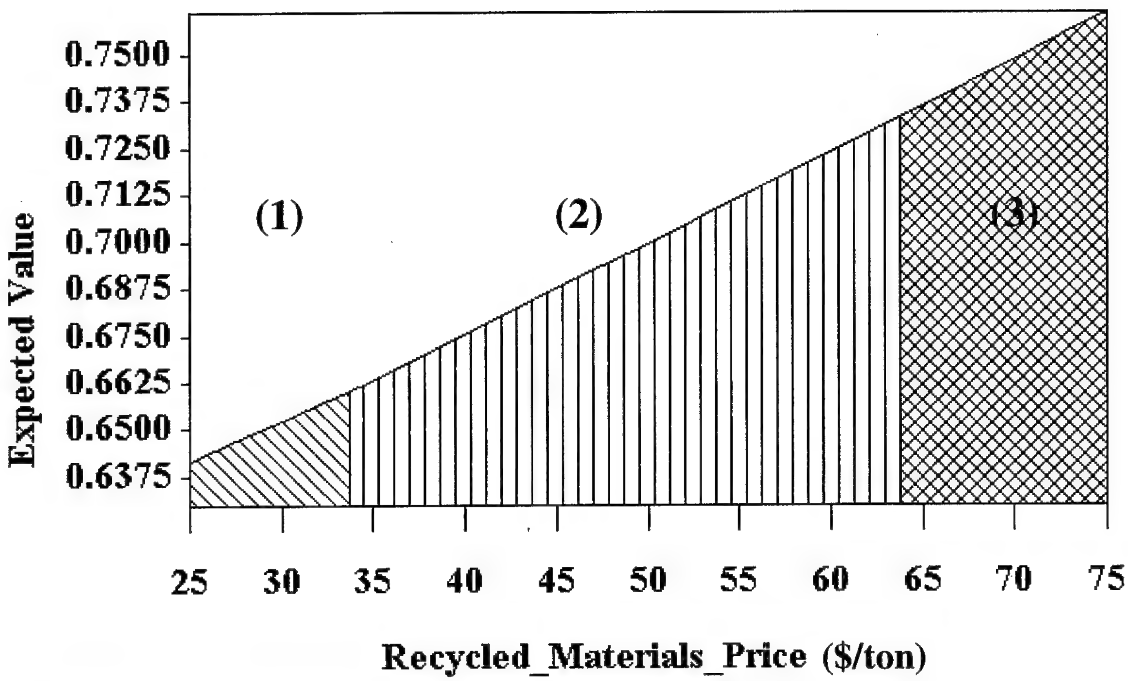

Figure 11. Rainbow Diagram for Recycled Materials Price

The regions depicted in Figure 11 denote the following policy changes:

(1) Change Source Reduction from "None" to "Regulation", change occurs at $34.50
(2) No change -- optimal decision policy
(3) Change Residential Recycling from "Central" to "Satellite", change occurs at $64.25

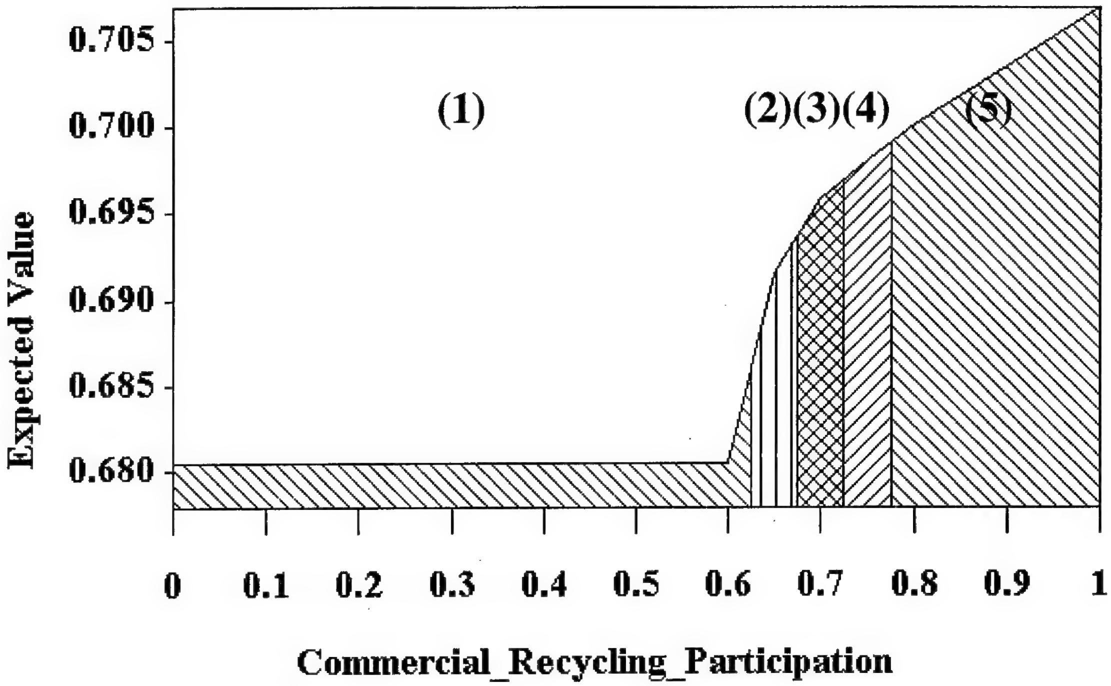

Figure 12. Rainbow Diagram for Commercial Recycling Participation (Commingled)

The regions depicted in Figure 12 denote the following policy changes:

(1) Change Source Reduction from "None" to "Combination", change Commercial Recycling from "Commingled" to "Separated", change Residential Recycling from "Central" to "Commingled", change Commercial Composting from "None" to "Central", change Residential Composting from "None" to "Central"
(2) Closer analysis needed, see Figure 13
(3) Closer analysis needed, see Figure 13
(4) Closer analysis needed, see Figure 13
(5) No change -- optimal decision policy

Figures 11 and 12 further illustrate the need to model these variables as uncertain events. Figure 11 depicts that as the price the base receives for the sale of its recyclable materials varies from its current level of $50 per ton, the optimal decision policy will also change.

Specifically, if the price drops to about $35 per ton, the decision policy would show a change from no source reduction to an emphasis on regulation to promote source reduction. On the other end of the spectrum, as the price increases to $65 per ton, the decision switches to satellite rather than central collection of residential recyclable materials. Figure 12 shows that as the commercial recycling participation rate drops from its expected level of 78 percent, the decision policy will change several times dependent upon the actual participation level. In fact, as the participation rate drops towards 60 percent, numerous different decision policies are shown to be optimal, as depicted in Figure 13.

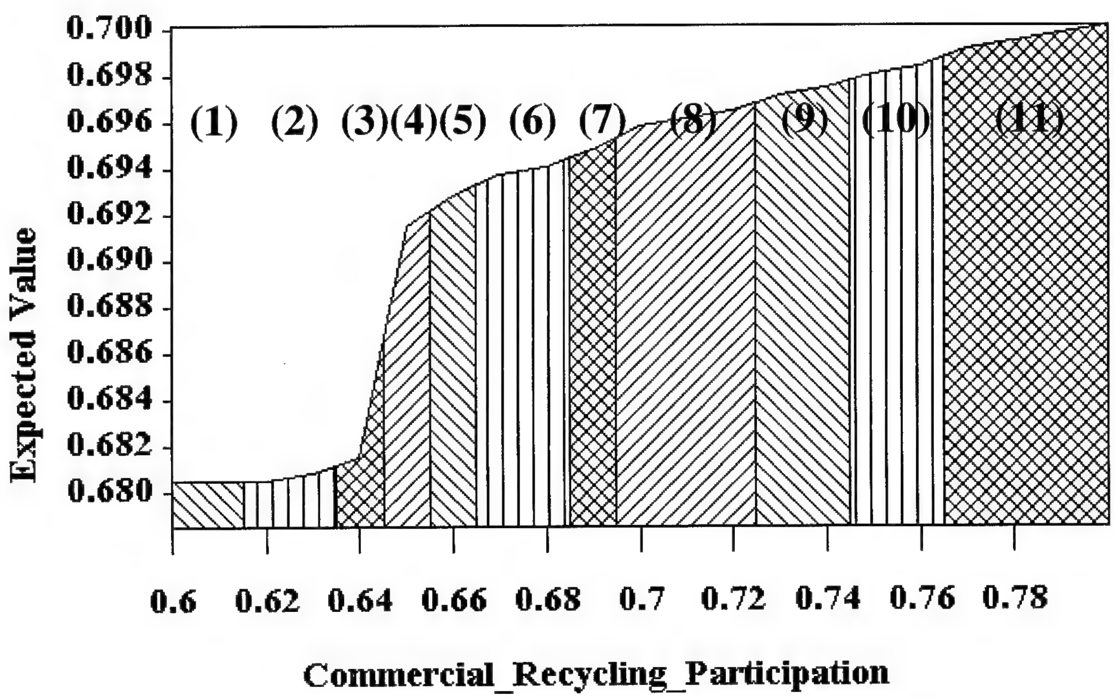

Figure 13. Rainbow Diagram for Commercial Recycling Participation (Commingled, 60% to 80%)

While each of these regions denotes a different decision policy, it is equally important to recognize where the decision change occurs. With this knowledge, the decision maker can decide whether or not it is necessary to determine which decision policy correlates to which participation rate. Note that region (1) of Figure 12 has different alternatives for every decision than the optimal solution. This is due to the numerous policy changes that are depicted in Figure 13. For the commingled commercial recycling participation rate, decision policy changes occur at the following values:

(1) Change occurs at 0.617
(2) Change occurs at 0.633
(3) Change occurs at 0.641
(4) Change occurs at 0.649
(5) Change occurs at 0.663
(6) Change occurs at 0.689
(7) Change occurs at 0.697
(8) Change occurs at 0.722
(9) Change occurs at 0.742
(10) Change occurs at 0.764
(11) Optimal decision policy

While sixteen variables considered in the value sensitivity comparison are shown to have no significant impact on the outcome of the model, fifteen of those are dependent upon conditioning events. Because each of these variables has at least one conditioning state where the variable does have a significant impact on the solution (with the exception of the composting participation variables), each of those are modeled with uncertainty. The lone exception is the percentage of total waste that is

generated in the commercial areas of base. Varying this level between 60 and 90 percent showed no change in the overall decision policy, and therefore was hard-coded into the model as 75 percent.

Additional sensitivity analysis was conducted on the weights of the three objectives, using the stochastic model. This analysis was conducted by holding the weight of one objective constant while allowing the others to vary among the remaining available weight. For example, the cost weight was held at 10 percent while the recycling and reduction weight varied across the remaining 90 percent. The following rainbow diagrams show the weight sensitivity when the profit, recycling, and reduction weights, respectively, are held constant at their suggested levels. Recall that the optimal deterministic decision policy is:

- Source Reduction Method: None
- Commercial Recycling Collection Method: Commingled
- Residential Recycling Collection Method: Central
- Commercial Composting Collection Method: None
- Residential Composting Collection Method: None

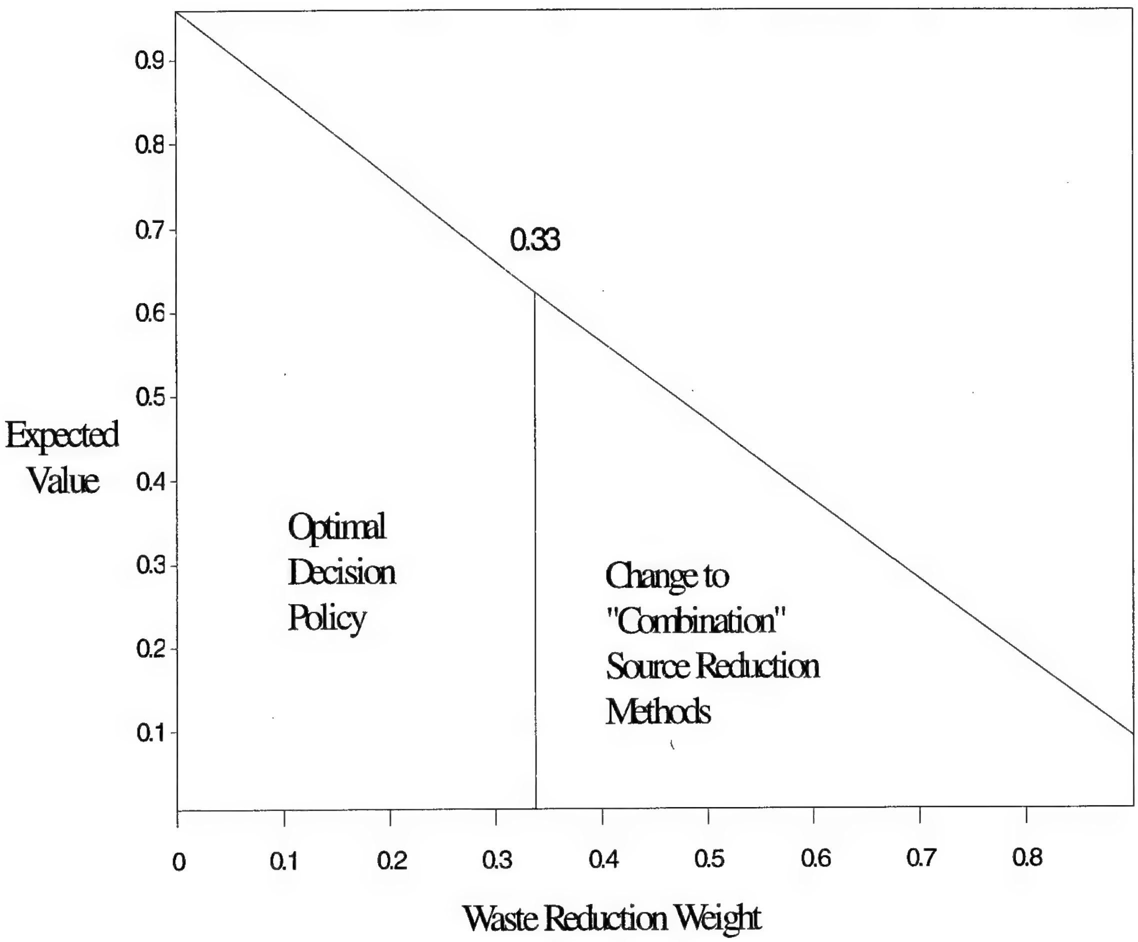

Figure 14. Rainbow Diagram of Waste Reduction Weight, Holding Profit Weight Constant at 10%

Figure 14 depicts that, holding the profit weight constant at 10 percent, the optimal decision policy changes to require a combination of source reduction methods rather than no source reduction when the reduction weight exceeds 33 percent.

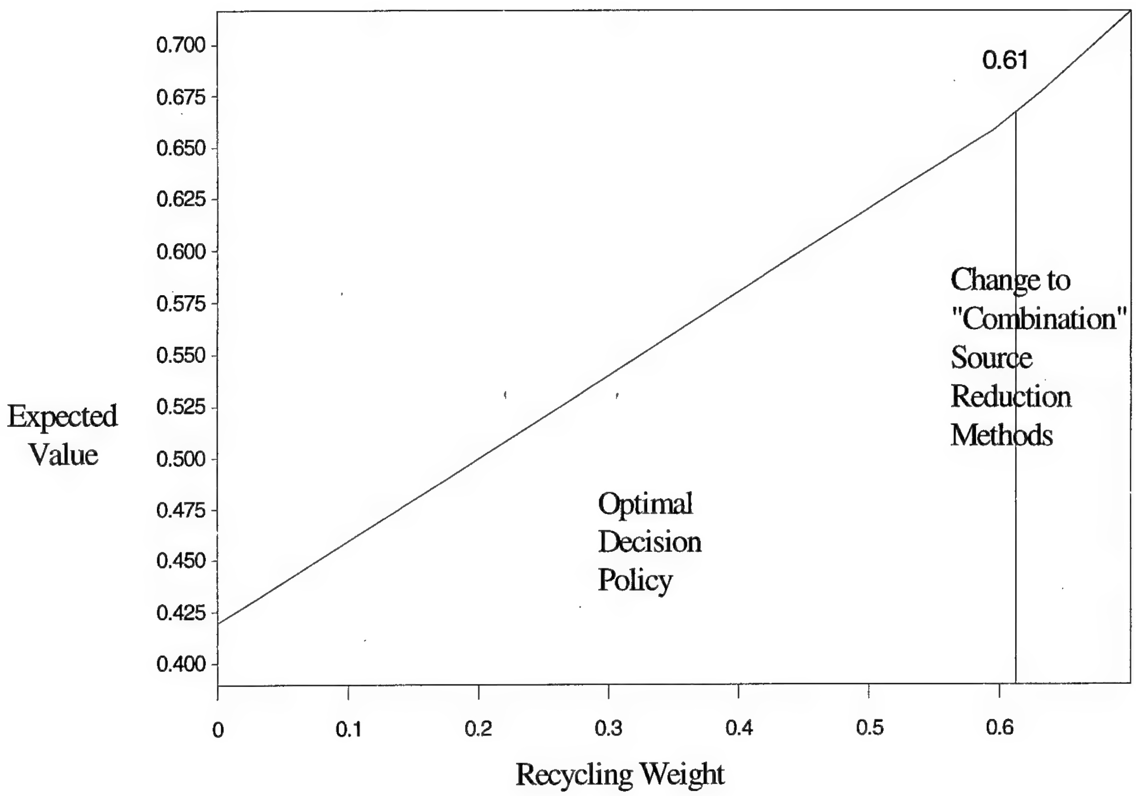

Figure 15. Rainbow Diagram of Recycling Weight, Holding Waste Reduction Weight Constant at 30%

Figure 15 shows that increasing the recycling weight above 61 percent, while holding the waste reduction weight constant at 30 percent, also results in a decision change to reflect a need for a combination of source reduction methods rather than the current optimal policy of no source reduction methods.

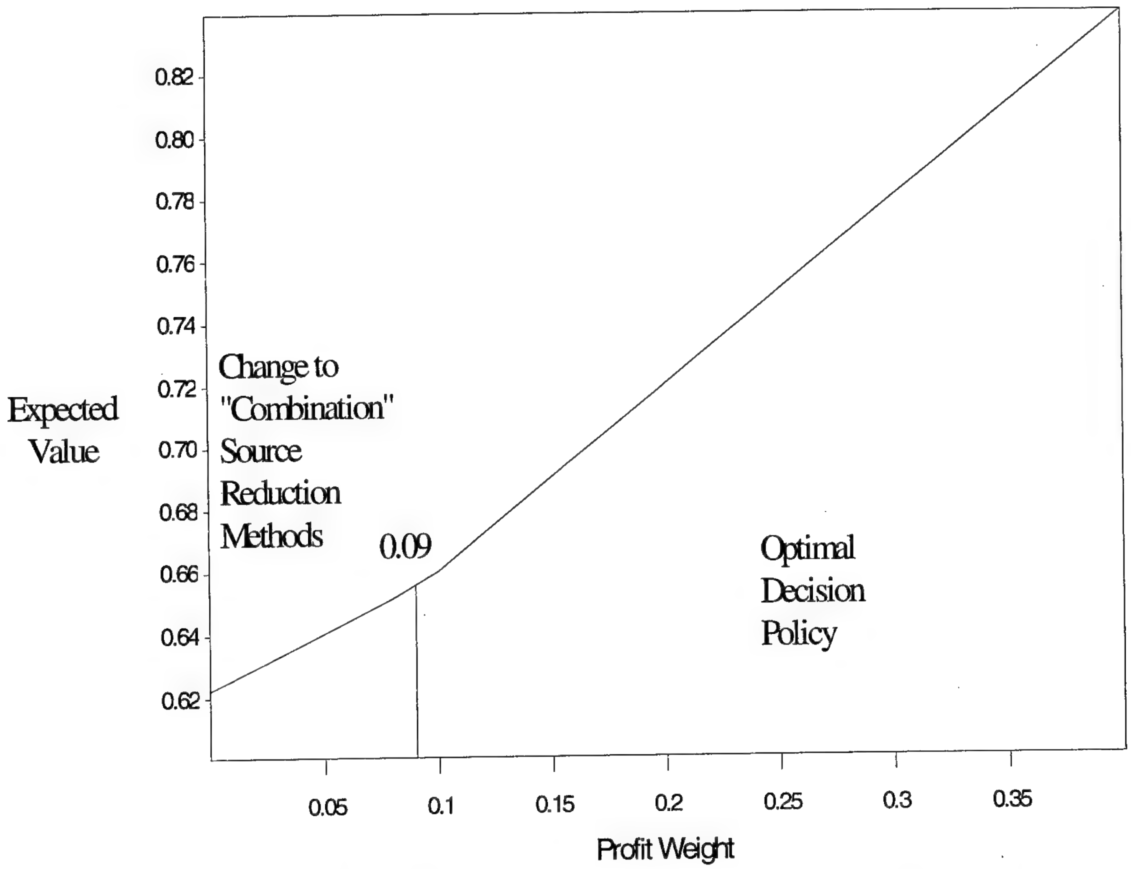

Figure 16. Rainbow Diagram of Profit Weight, Holding Recycling Weight Constant at 60%

Figure 16 again shows a decision change from the optimal policy to a combination of source reduction methods. This change occurs when the weight of the profit objective drops from 10 percent to 9 percent, holding the recycling weight constant at 60 percent.

These three graphs indicate that a slight change in the objective weights would most likely result in a change in the recommended decision policy from no source reduction methods to a combination of source reduction methods, including education, regulation, and new equipment procurement. This analysis indicates that the weights of

the three objectives should be further reviewed to ensure they are accurate, due to their collective impact on the outcome of the model.

Final Decision Analysis

Having verified which variables should and should not be modeled with uncertainty through sensitivity analysis, the next step is to actually model these variables as uncertainties. This model results in a slightly different optimal waste management policy than was obtained by the initial decision analysis. This is due to the addition of uncertain events in the problem that affect the outcome. The optimal policy includes commingled curbside collection of recyclable materials in both the commercial and residential areas of the base, satellite collection of compostable materials for both areas of the base, and no use of source reduction methods. The overall score obtained by this policy is approximately 0.620. This score reflects a policy that produces a recycling level of approximately 61.1 percent of all waste generated annually, a waste reduction of just 9.9 percent from the baseline, and a program cost of approximately $151,000 per year. (Note that the waste reduction level does not meet the Air Force objective of 50 percent.) This optimal policy is shown in Figure 17. The overall score is driven by the recycling level that is achieved. Because the recycling level is greater than 50 percent, the utility score for that objective is 1. Since

the weight of the recycling objective is 0.6, the recycling level then accounts for 0.6 of the 0.620 that is achieved by the program. Therefore, it is shown that the waste reduction and cost objectives have little effect on the overall value of the selected decision policy.

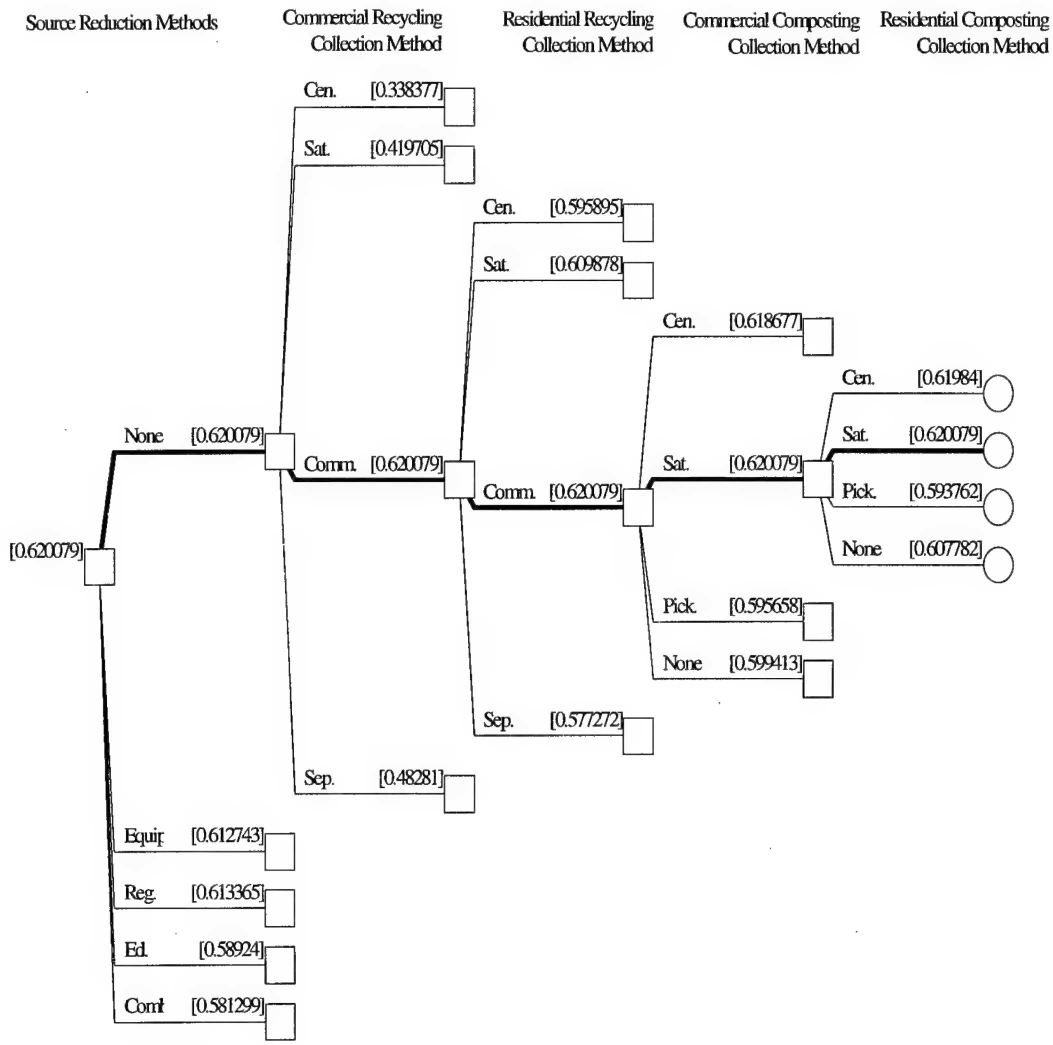

Figure 17. Optimal Decision Policy With Uncertain Events

It is also important to recognize the importance of measuring the various alternatives with respect to a single

measure that is inclusive of all objectives. The optimal policy depicted in Figure 17 is determined by measuring the alternatives using a single value that includes all three objectives: recycling level, waste reduction, and cost (or profit). Using the model to optimize the individual objectives results in different outcomes. Figure 18 shows the optimal strategy when optimizing the recycling level; Figure 19 the waste reduction level; and Figure 20 the program profit. These optimal strategies are determined by optimizing only the selected objective in the DPL™ model, rather than the overall score based on all three objectives.

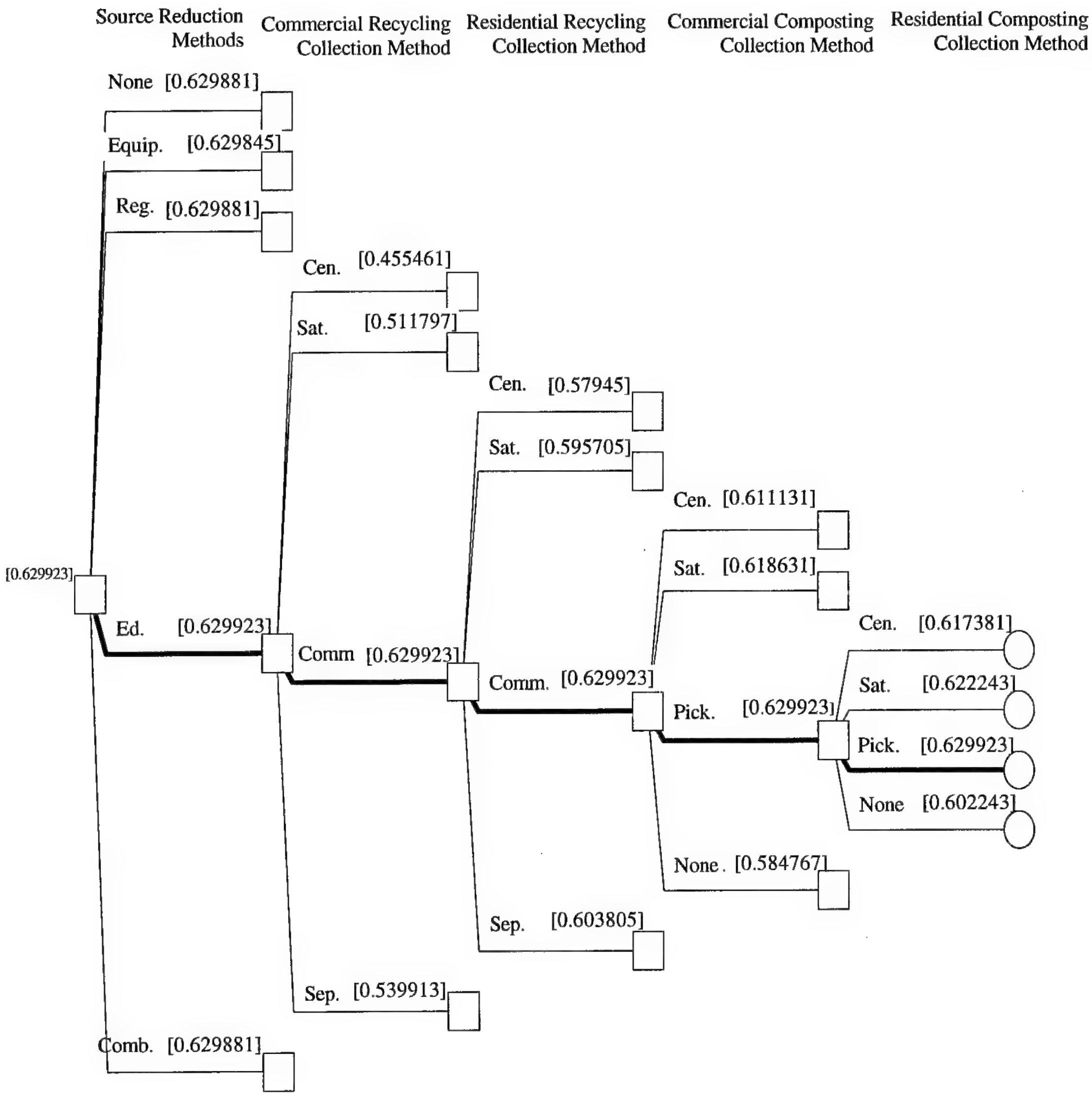

Figure 18. Decision Policy to Optimize Recycling Level (%)

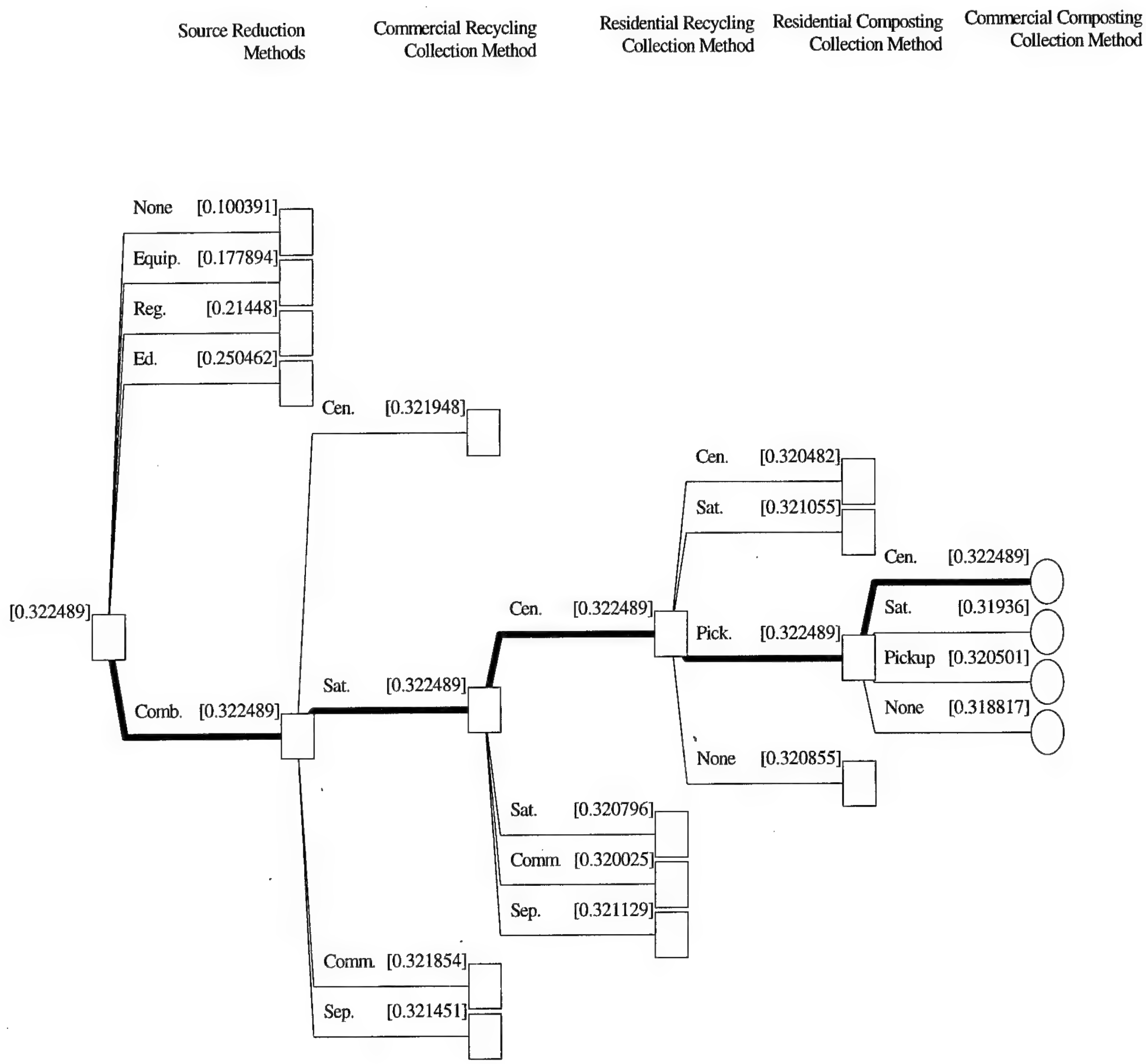

Figure 19. Decision Policy to Optimize Waste Reduction Level(%)

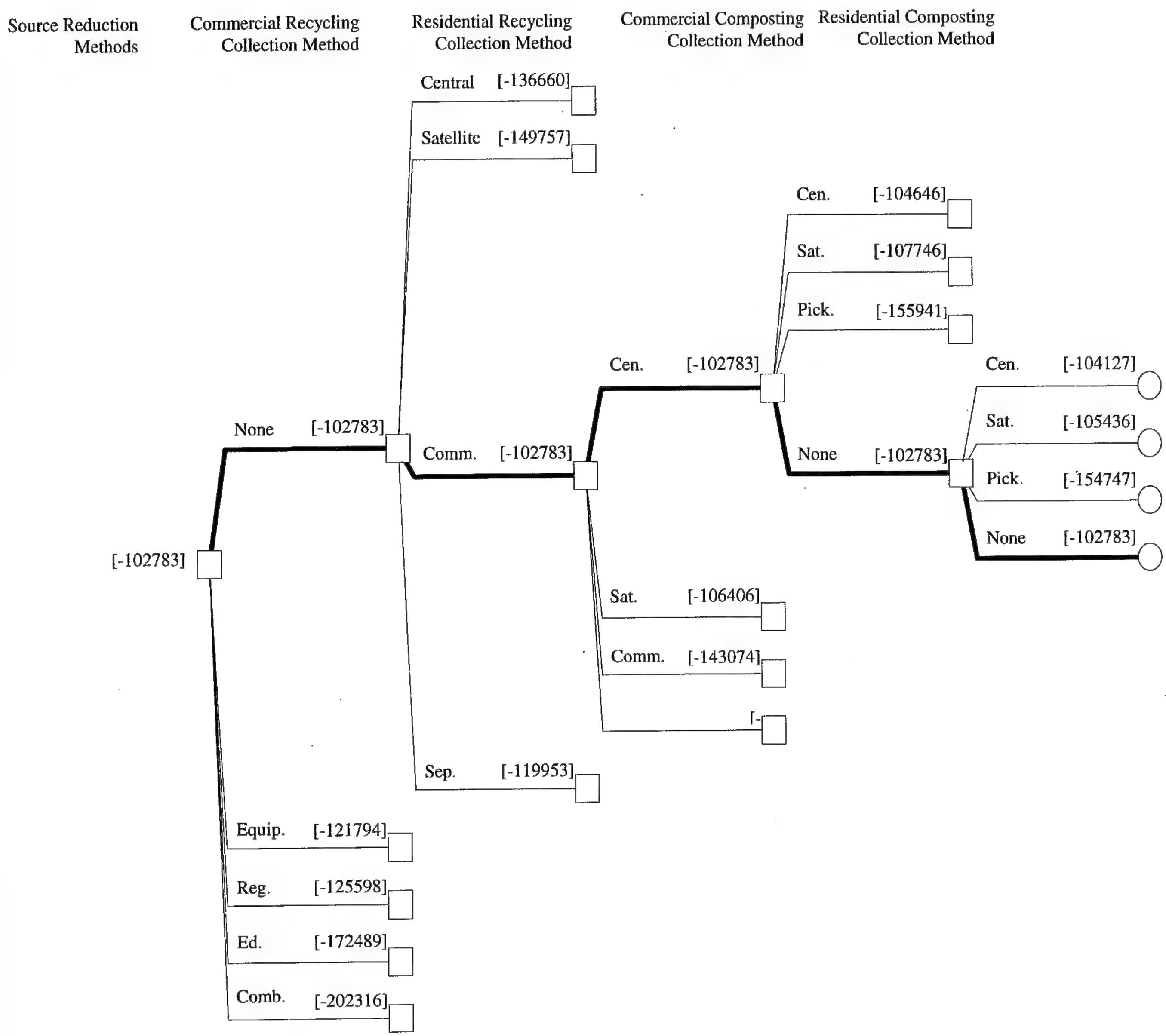

Figure 20. Decision Policy to Optimize Program Profit ($)

The cumulative risk profile of the optimal solution (considering all three objectives) is depicted in Figure 18. The vertical line indicates the expected value, or overall score, of the optimal decision policy. The ragged line shows the probability at which the decision maker can expect

to receive the corresponding score or lower. For example, the graph indicates that the selected decision policy has a 50 percent chance of returning an overall score of approximately 0.70 or less, while there is only a 10 percent chance of returning a score of 0.30 or less.

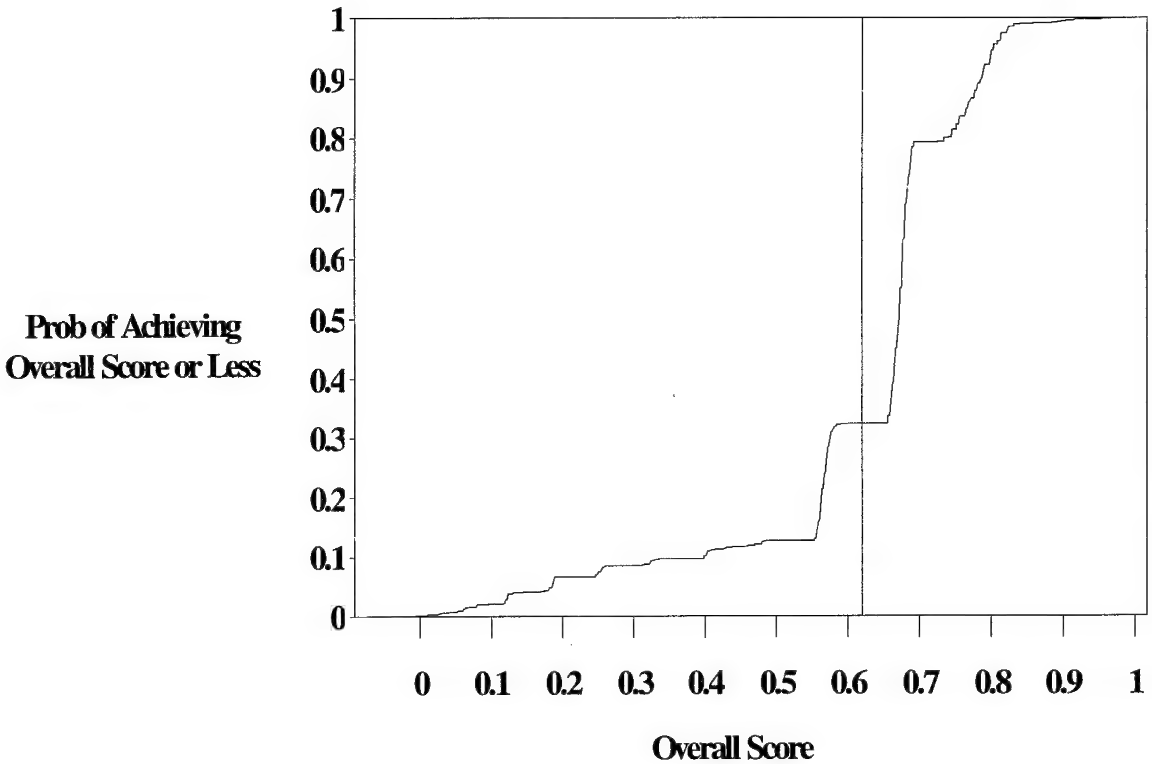

Figure 21. Cumulative Risk Profile for Optimal Decision Policy

The cumulative risk profile can also be separated by the various event states to show whether or not some alternatives are dominated by others. Figures 22 through 26 show these profiles for each of the five decisions: Source Reduction Methods, Commercial Recycling Collection Method, Residential Recycling Collection Method, Commercial Composting Collection Method, and Residential Composting

Collection Method. By analyzing these cumulative risk profiles, it is possible to determine whether or not any single strategy for any decision is the best selection over the entire range of possible outcomes. Each of these graphs, considered separately, shows that no single strategy, for any decision, is dominant over all others, or is dominated by all others, over the entire range of possible outcomes. In other words there is no stochastic dominance among the alternatives. Further, no stochastic dominance implies no deterministic dominance among the alternatives.

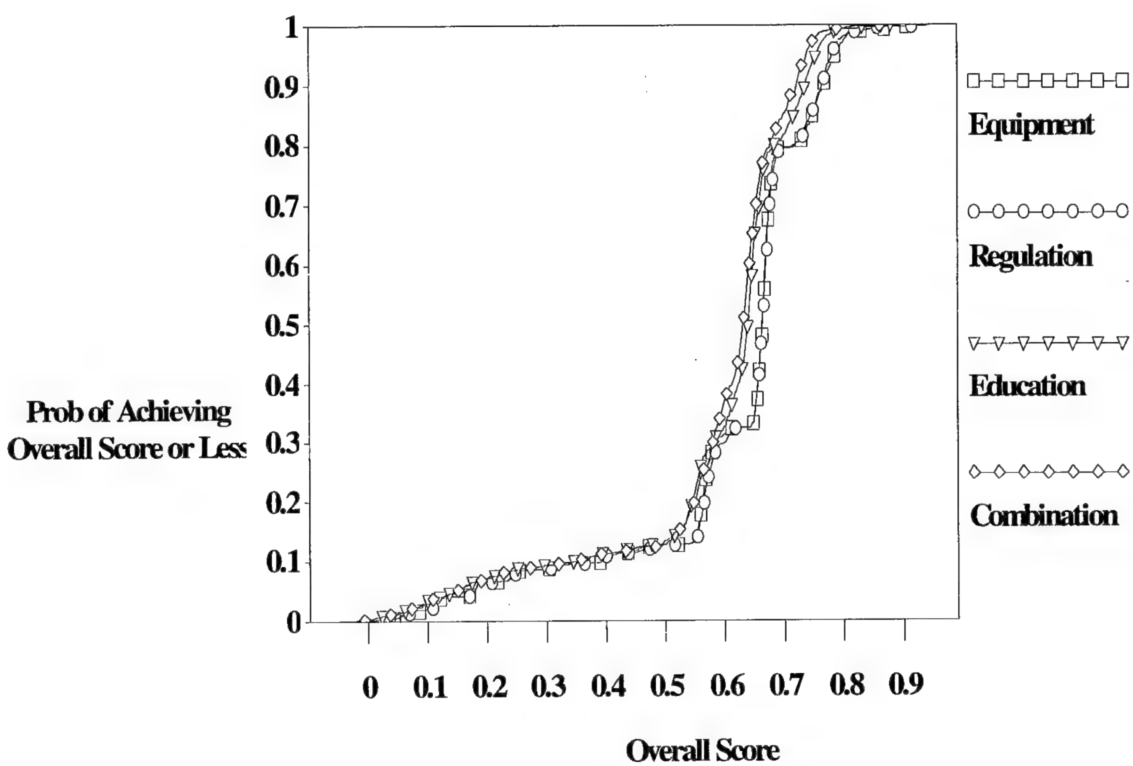

Figure 22. Cumulative Risk Profile, Source Reduction Methods

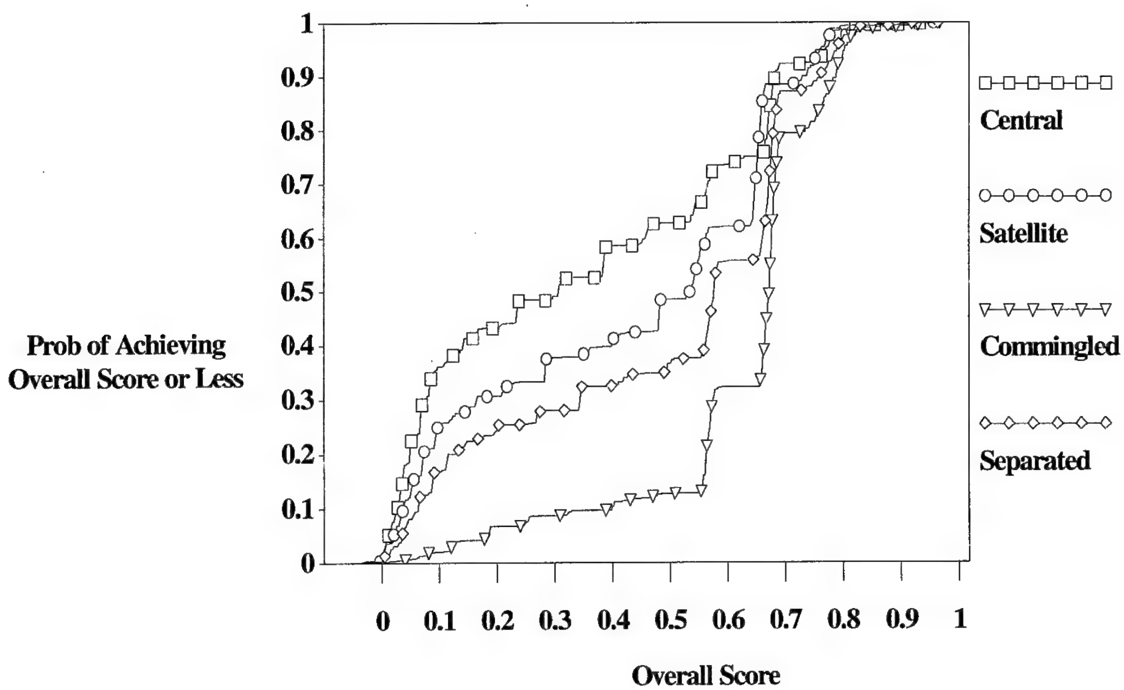

Figure 23. Cumulative Risk Profile, Commercial Recycling Collection Method

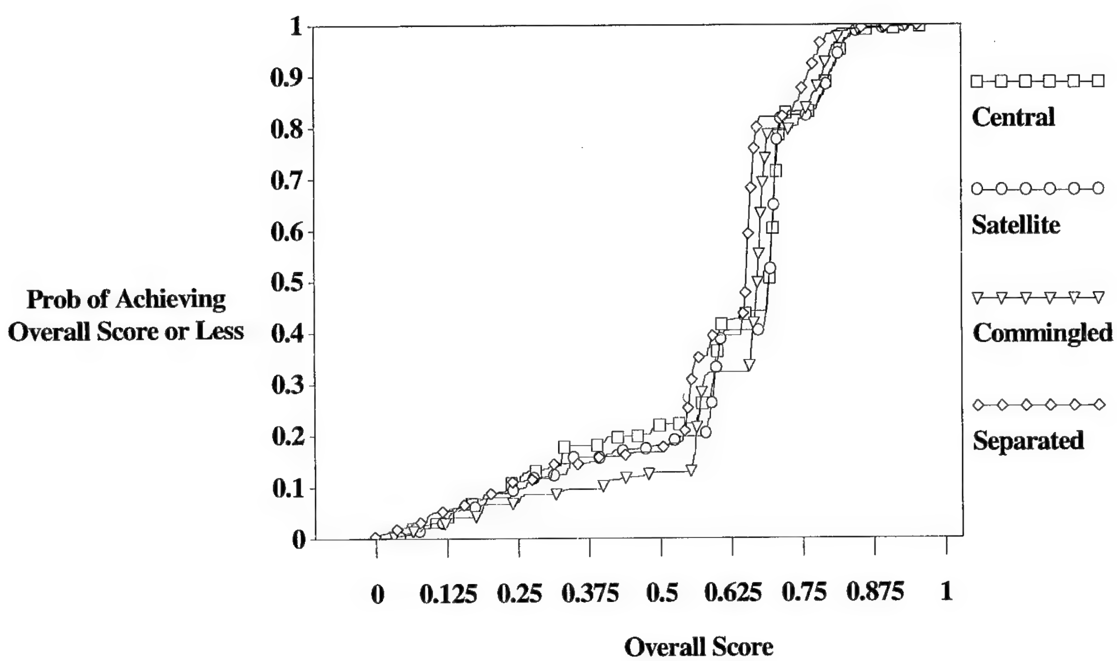

Figure 24. Cumulative Risk Profile, Residential Recycling Collection Method

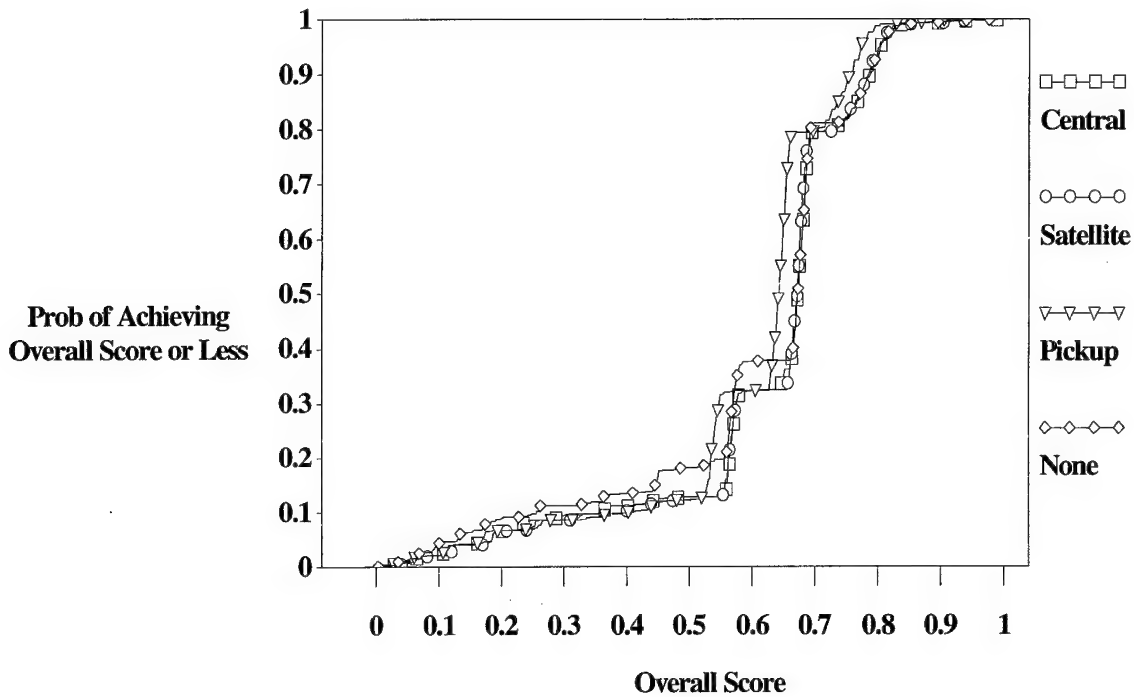

Figure 25. Cumulative Risk Profile, Commercial Composting Collection Method

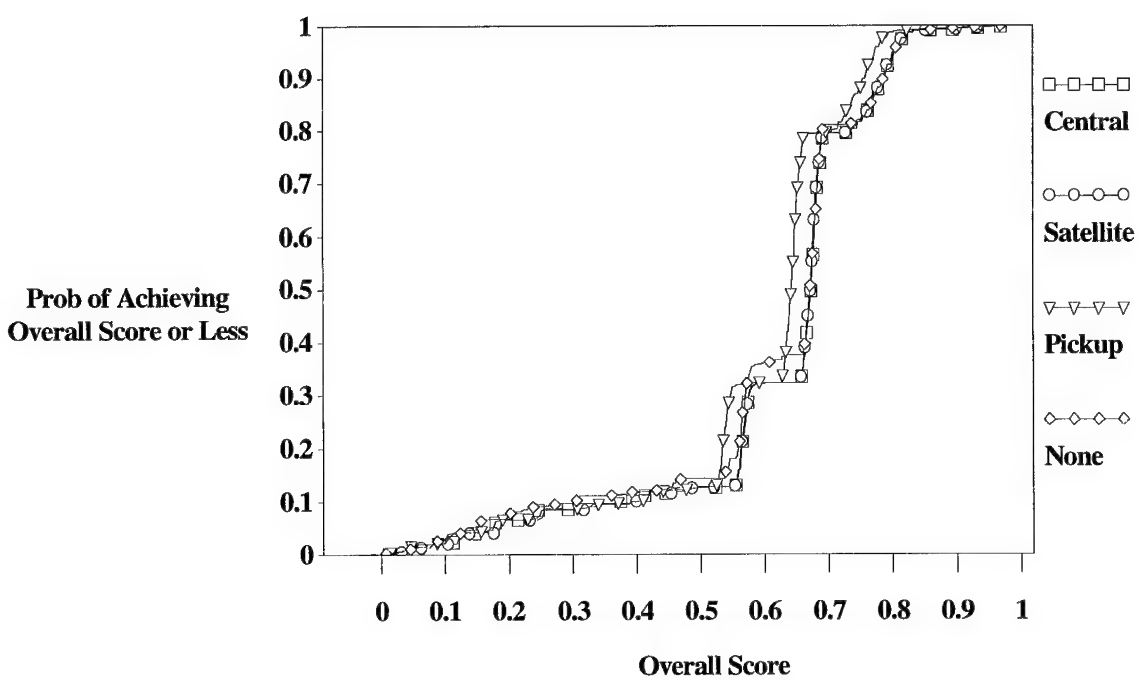

Figure 26. Cumulative Risk Profile, Residential Composting Collection Method

Analysis of the current, or baseline, decision policy, using the stochastic model, yields significantly lower scores than the recommended policy. The baseline policy is:

- Source Reduction Method: Education
- Commercial Recycling Collection Method: Separated
- Residential Recycling Collection Method: Commingled
- Commercial Composting Collection Method: Pickup
- Residential Composting Collection Method: Central

This policy yields an overall score of 0.436, while the recommended policy, as stated earlier, yields an overall score of 0.620. This difference indicates that the overall utility to the decision maker of the recommended decision policy is more than 40 percent better than the current policy.

The differences between the decision policies are further illustrated by a comparison of the optimal results obtained through deterministic and stochastic analysis and the results reflecting the baseline policy. Table 5 shows the optimal deterministic and stochastic policies, as well as the baseline strategy. Table 6 then compares the outputs of each of these strategies.

Table 5. Comparison of Strategies

Strategy	Source Reduction Method	Commercial Recycling Collection	Residential Recycling Collection	Commercial Composting Collection	Residential Composting Collection
Deterministic	None	Commingled	Commingled	None	None
Stochastic	None	Commingled	Commingled	Satellite	Satellite
Baseline	Education	Separated	Commingled	Pickup	Central

Table 6. Comparison of Strategy Results

Strategy	% Recycled	% Reduced	Annual Cost	Overall
Deterministic	50.7	9.8	$103,000	0.699
Stochastic	61.1	9.9	$151,000	0.620
Baseline	52.7	24.6	$282,500	0.436

While the deterministic analysis achieved the best overall results, it is not a feasible strategy as there is a great deal of uncertainty inherent in the problem. Note that in comparing the other two strategies, each achieves the 50 percent recycling objective which has the greatest associated weight. Also note that optimal policy has an expected recycling level considerably higher than 50 percent, which indicates there is less chance that the policy will return a recycling level short of the 50 percent goal. Also notice that the recommended policy has a considerably lower annual cost than the baseline policy. The scores for the third objective, waste reduction, provide some helpful insights into the modeling of the problem. While neither strategy meets the 50 percent reduction goal, the baseline policy results in a considerably higher waste

reduction level, but a considerably lower overall score. This is a direct result of the utility function that defines the reduction goal. It indicates that little value is gained from any policy until it reduces waste by 35 to 40 percent. Therefore, it is not cost effective to engage in any source reduction methods unless those methods can reach or nearly reach the 50 percent waste reduction goal. Also, if it becomes important to the decision maker to achieve the highest possible recycling levels, rather than simply exceed 50 percent, the selected decision policy is again considerably better than the baseline policy.

Further analysis of the results produces additional insights concerning the problem. Specifically, it is possible to discover which decision has the greatest impact on the overall score of any decision policy. Recall that the optimal decision policy returns an overall score of 0.620. By holding four decisions constant at their optimal policy alternatives and varying only the fifth decision, it is possible to show the range of scores that can result from varying that single decision. Table 7 shows the worst case scenario and associated score for each of the five decisions, as well as the variation from the optimal policy score.

Table 7. Overall Impact of Decisions

Decision	Worst Case Scenario	Worst Case Score	Change from Optimal
Source Reduction Methods	Combination	0.582	0.038
Comm. Recycling Collection Method	Central	0.338	0.282
Res. Recycling Collection Method	Separated	0.577	0.043
Comm. Composting Collection Method	Pickup	0.595	0.025
Res. Composting Collection Method	Pickup	0.594	0.026

This indicates that the commercial recycling collection method decision has the greatest impact on the overall score of any decision policy. Using this information, it is possible to qualify the worst case scenario when the commercial recycling decision is held constant as commingled collection at the office, which is the optimal alternative. This worst case decision policy is:

- Source Reduction Method: Combination
- Commercial Recycling Collection Method: **Commingled**
- Residential Recycling Collection Method: Separated
- Commercial Composting Collection Method: None
- Residential Composting Collection Method: None

The overall expected score of this decision policy is 0.491, and has an expected recycling level of 53.1 percent, a waste reduction level of 31.9 percent, and a program cost of about $275,500. This shows that if the commingled commercial recycling collection method is selected, even using the

worst case scenarios for the other problem decisions, the base can expect to meet its 50 percent recycling goal. This is depicted in the cumulative risk profile in Figure 27. It also indicates, however, that there is about a 35 percent chance of this decision policy returning a recycling level of 50 percent or less.

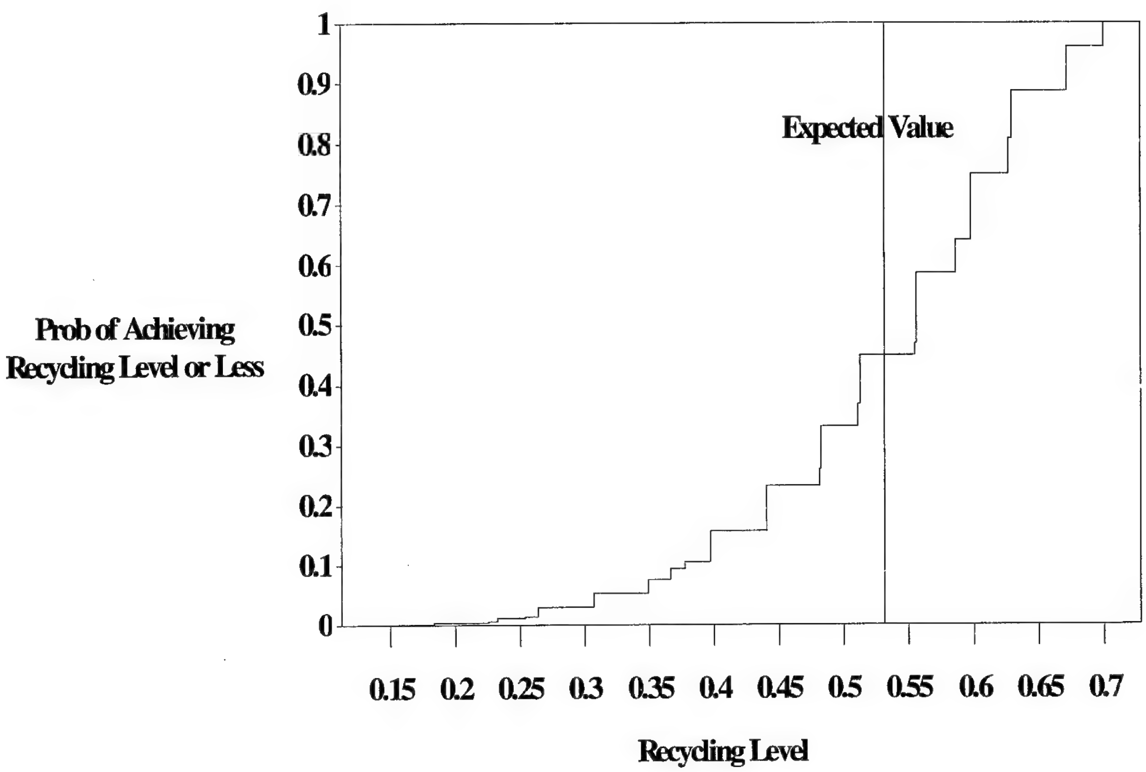

Figure 27. Cumulative Risk Profile for Recycling Level, Worst Case Scenario

If, however, the commercial recycling collection method is held constant as commingled and the model optimizes the remaining decisions, the probability of achieving a recycling level less than 50 percent falls to under 15 percent (shown in Figure 28). Also, the expected recycling

level increases from 53 percent to 61 percent (indicated by the vertical lines in Figures 27 and 28, respectively).

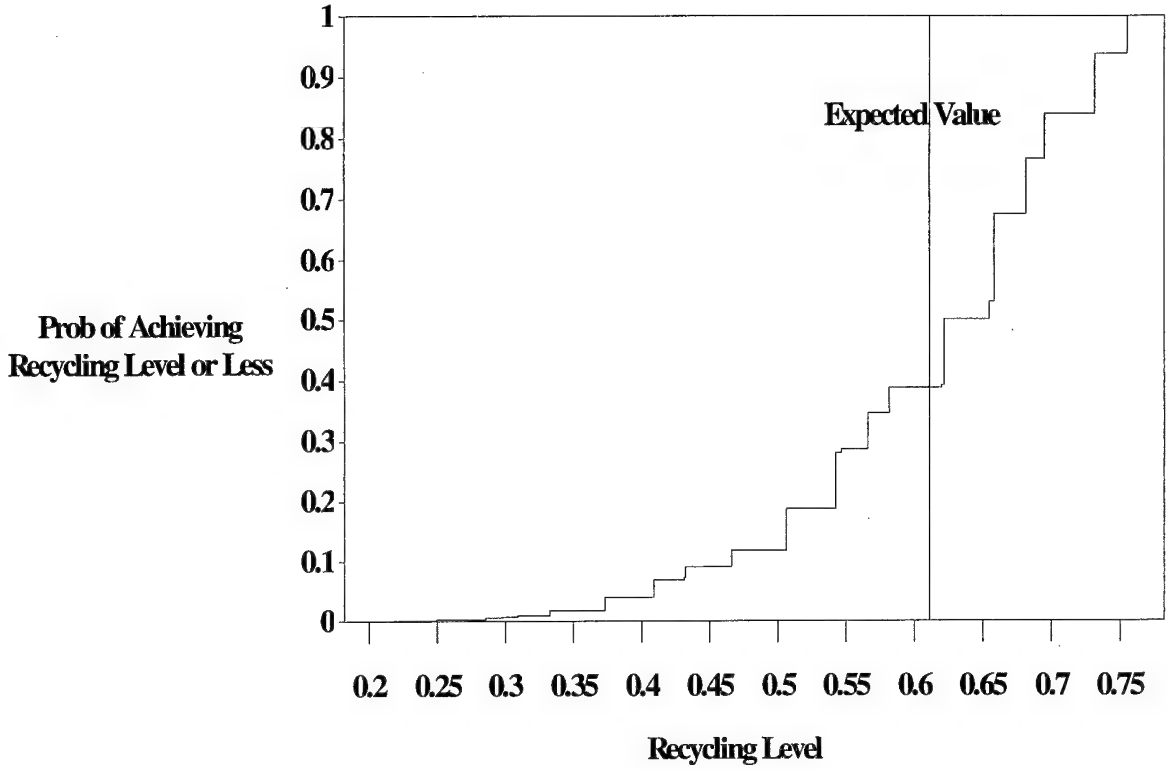

Figure 28. Cumulative Risk Profile for Recycling Level, Optimal Scenario

It is also important to recognize, however, that the "worst case scenario" policy, when holding the commercial recycling collection method as commingled, is closer to achieving the 50 percent reduction goal than the selected "optimal" policy. The overall score is low because the recycling level is close to the 50 percent threshold, meaning there is a greater probability of the policy not generating a 50 percent recycling level. Also, the added cost of incorporating a combination of source reduction methods has a greater effect on the overall score than the

added utility of increasing from 10 percent to 30 percent reduction.

Summary

Using the information presented in this chapter, it is possible to draw several conclusions concerning municipal solid waste management and make several recommendations to the decision makers at Wright-Patterson AFB.

For installations in general, it is important to realize that commercial recycling drives the base's ability to meet its recycling goals. This is due to the fact that much more waste is generated in commercial areas of base than in residential, and much more waste can be recycled than can be composted. Also, waste reduction goals are difficult to meet, and therefore require intensive effort. There are numerous methods that can be used to motivate source reduction, and it is important to thoroughly investigate as many feasible alternatives as possible in order to select the methods which are most likely to help the base meet its goals.

For Wright-Patterson AFB, the recommended policy includes commingled collection of recyclable materials in all areas of base, and satellite collection points for compostable materials. The best overall score also includes no source reduction, which is a result of the waste reduction utility function. This policy will likely enable WPAFB to meet its 50 percent recycling goal at a reasonable

cost, but because the waste reduction goal cannot be met regardless of the effort put forth, it is not cost effective to engage in any source reduction activities. However, this policy may be considered politically incorrect, and for that reason the decision makers at WPAFB may elect to give up some additional cost in order to motivate some source reduction.

Further discussion of these conclusions and recommendations will be presented in the following chapter.

Chapter V. Conclusions and Recommendations

Overview

The purpose of this research effort was to develop a decision support model for use at Air Force installations to aid the decision maker in selecting a municipal solid waste management policy for the base. This chapter will discuss conclusions drawn from the research. First, the modeling and results will be summarized. Second, insights and recommendations concerning the implementation of a municipal solid waste management policy will be offered. Third, opportunities for future research in this area will be suggested. Finally, a brief summary of the research will be presented.

Summary of Modeling and Results

Environmental managers at Air Force installations must make numerous decisions regarding the management of waste generated at the installation. Municipal solid waste management policies are implemented in an effort to meet three objectives: an overall reduction of 50 percent (from a 1992 baseline amount) in the amount of waste generated by 1999, 50 percent recycling of the waste that is generated by 1999, and minimal cost program. The waste management policy that the decision maker selects must focus on four methods of waste management that are alternative to landfilling.

They are source reduction, recycling, composting, and incineration.

The modeling of this problem involved a decomposition of the problem so as to model each of these four areas individually. In the area of source reduction, the decision maker must consider where to direct funds in an effort to reduce the amount of waste generated at the base. For recycling and composting, the decision maker must select collection methods for each which will maximize the amount of waste that is actually recycled and/or composted while minimizing the associated costs. This also involves considering separate collection methods for the commercial and residential areas of base, due to the different composition of the waste as well as the varying participation rates. The decision maker may also have to consider whether or not waste should be incinerated prior to disposal at a landfill.

In selecting the best waste management policy, the decision maker must consider each of these areas with respect to their impacts on the overall objectives of the program. There are, however, many factors that are beyond the control of the decision maker that also have an impact on the achievement of these objectives. The waste generation rates that stem from various source reduction methods can be approximated, but there is a great deal of variability in those levels. The individual participation

rates that define the actual amount of waste that is recycled can also be approximated, but could vary anywhere from 0 to 100 percent. The revenue realized from the sale of recyclable materials is highly dependent upon market conditions which constantly fluctuate.

There are also many variables which are specific to the base being considered. The first of these involves the facilities available for use by the base. Composting facilities and incinerators are not as commonplace as recycling plants and landfills, so composting and/or incineration may not always be an option for the base environmental manager. Therefore, each base may have a different set of feasible collection and disposal alternatives. The cost of various collection programs is dependent upon base location as well as the program that is currently being used. The amount of waste generated is also specific to the base as it is dependent upon the base population.

It is also necessary to properly consider each of the objectives. First, an appropriate representation of the value to the decision maker of each objective must be developed. Then, the three objectives must be weighted to reflect the relative importance of each. Finally, the three objectives must be combined to produce a measure that compares the various strategies.

Having considered all of the variables that are important to selecting a waste management policy, and having developed a measure by which to select the best policy, the alternatives available to the environmental managers at Wright-Patterson Air Force Base (WPAFB) were analyzed. The results of the analysis show that the best overall score the base could achieve stems from a reduction in waste generation of approximately 10 percent from its 1992 level and a recycling level of approximately 61 percent at an annual cost of about $150,000. These results are obtained through the use of commingled curbside collection of recyclable materials in both the commercial and residential areas of base, satellite collection of compostable materials both areas of base, and no allocation of funds to support source reduction methods on base. Further, this policy reflects only a 15 percent chance that the recycling goal will not be met. Also, since there is no policy which can achieve the 50 percent reduction goal, and due to the shape of the reduction utility curve, it becomes unimportant for the decision maker to pursue the more costly source reduction alternatives. It is important to remember that this solution is specific to the weightings, costs, and assumptions provided by the environmental managers at WPAFB, but model could easily be adjusted for use at other Air Force installations.

Insights and Recommendations

The driving force behind the success of a waste management program is participation by the individual. As participation rates fall, waste generation rates increase while the amount of waste recycled and/or composted decreases. Specifically, the participation of base personnel in recycling programs drives the ability of the base to meet its 50 percent recycling objective. The environmental manager must therefore make decisions regarding waste management that will encourage the individual to participate. Research conducted at WPAFB indicates that people will be more apt to participate in waste reduction and recycling if they in turn receive something for their effort. That reward could be as simple as a good feeling because they are leaving a better environment for their children or the recreation value gained because revenue from recycling can be used for base MWR activities (Still, 1996). Another factor that influences individual participation is convenience -- the easier it is to reduce or recycle, the more likely the individual will try (Still, 1996).

In successfully implementing a program, it is vital to consider the individual when making decisions. The environmental manager should use education programs to impress upon the individual the importance of his or her role in the environment. It is also important to make

reduction and recycling as easy as possible for the individual, through the use of convenient collection programs. If the individual understands how important it is to be environmentally conscious, and it is easy to participate in environmental programs, then a waste management policy can potentially achieve its goals.

Future Research

Several aspects of this research could be considered further. Analysis of participation rates clearly lends itself to future research. While studies have been conducted to measure the individual's willingness to participate (Still, 1996), it may be important to determine the relationship between awareness, convenience, and actual participation. Specifically, it may be helpful to determine the level of awareness that is associated with each level of participation.

The participation rates used in this modeling effort should be re-evaluated. They are based primarily upon the experience of the environmental managers at WPAFB and the participation measured in various programs currently in practice across the United States. Therefore, these rates may not be valid at other Air Force installations. In addition, the only values that are used are average participation rates, with the low and high rates being fixed at 0 and 1, respectively. Further research may show that

there are tighter bounds on the participation rates that are applicable to the problem, or perhaps another distribution could be used to model the participation rates.

Finally, the relative weights of the objectives, as well as the utility functions of each objective, may differ from base to base. A survey of Air Force leadership at a higher level might better define the utility functions and objective weights so that Air Force, rather than individual, values are represented. The current utility functions indicate that the base environmental manager considers the waste management program equally successful whether the base recycles 50 percent of its waste or 100 percent of its waste. Further research or additional consultations may result in a change from this belief. Also, the waste reduction goal of 50 percent seems to be virtually unobtainable, yet the decision maker receives very little value, with respect to waste reduction, until a program reaches 40 percent waste reduction. A vastly different recommendation may be in order if this utility function were changed to a linear function. Also, in different environments at different bases, cost may have an increased or even a reduced role in policy selection.

Research Summary

The Air Force has recently redefined its municipal solid waste management goals to include waste reduction of

50 percent and recycling levels of 50 percent at a minimum cost. This research effort has developed a model, which reflects the decisions made by an environmental manager at the base level, that will aid the decision maker in selecting the best waste management policy to meet those goals.

Appendix A. Decision Analysis

Decision Analysis Process

The process of decision analysis can be described in seven steps (Clemen, 1991: 7):

- Identify the Problem
- Identify the Objective(s) and Alternatives
- Decompose and Model the Problem
- Choose the Best Alternative
- Perform Sensitivity Analysis
- Decide if Further Analysis is Necessary
- Implement the Chosen Alternative

Because this process is iterative, the analyst is able to continually update the problem statement to keep pace with any changes that may arise. A change in the issues that surround the problem or in the decision maker's perception of the problem could potentially invalidate an analysis, if the analyst were not able to update the problem structure. The appropriate problem structure is the framework for a sound analysis.

Identifying the problem correctly is the most important step in any analysis. Without proper problem identification, any analysis performed could very well be irrelevant to the decision maker. It is also important for the analyst to recognize that the true problem to be addressed may not be intuitively obvious. Instead, the

problem initially diagnosed may simply be an indication of a more severe problem, and the analyst must discover what the underlying problem is.

Nearly as important as identifying the true problem is *identifying the objective(s) and alternatives.* Oftentimes the true objective of an analysis is not clearly stated, instead requiring a great deal of thought and consultation by both the analyst and the decision maker. Also, many times there are multiple objectives in a problem, and those objectives are sometimes conflicting. In addition to identifying these objectives, the analyst must also determine what alternatives are available for consideration in the problem. This too requires careful thought, as all possible alternatives must be taken into account. It is important to remember that the "do-nothing" approach is many times a feasible alternative.

Decomposing and modeling the problem is the next step in any analysis. By decomposing the problem, the analyst breaks the problem into smaller, more manageable subproblems. This allows the analyst to study each part of the problem separately, so as to gain a better understanding of the overall problem. Having decomposed the problem, the analyst must then model the problem. A well-built model that accurately captures the essence of the problem will usually yield a quick and accurate solution.

The primary goal of decision analysis is to *choose the best alternative*. But because the process is iterative, the "best" alternative may not always be immediately discovered. In fact, each iteration of the decision analysis process will likely eliminate some alternatives, while holding on to others for further consideration.

Sensitivity analysis is where the iterative nature of the process truly comes into play. Sensitivity analysis considers how changes in the model will affect the outcome of the model. Specifically, it measures which parameters have the greatest influence on the solution, and what degree of change in the various parameters might lead to a change in the optimal solution, or decision policy. One alternative may be preferred for one set of parameters, while slight changes to some of those parameters may yield a different solution. The results of this analysis can sometimes lead to exclusion of some parameters, or further study of others. In general, sensitivity analysis goes to improving the model.

Next, the decision maker and the analyst must *decide whether or not further analysis is necessary*. Until both agree that the analysis is complete, the process should be repeated. A complete analysis requires that the decision maker's preferences and values are fully and accurately modeled, that all alternatives are considered, and that all

available information was used in building the model or discarded as unnecessary.

Once the analysis is complete, the final step in the process is to *implement the chosen alternative*. This is simply acting upon the analysis results. While not actually a part of the analysis, this step is the ultimate measure of the correctness of the model. A good model will suggest an alternative that, when implemented, solves the stated problem and/or meets the desired objectives of the decision maker.

Decision Problem Elements

There are three elements in any decision problem: the decision that must be made, the uncertain events that affect the problem, and the outcome values that measure that measure each alternative.

The *decisions* to be made are the framework for any decision problem. The decision maker must have the control and the authority to make and eventually implement these decisions. A decision problem may have one or many decisions to be made. The decisions may have to be made sequentially or concurrently. In some cases the selected alternative of one decision may affect which decision needs to be made next, or it may affect which alternatives are feasible in that next decision. In other cases the decision maker may have to make several decisions which all affect

the final outcome, but which must all be made simultaneously.

Uncertain events are events that the decision maker cannot control, but are still vital to the outcome of the problem. In some cases the outcome of those events may be known before a decision must be made, but other times the outcome may not be known. Regardless of this, it is important that each uncertain event be modeled to reflect every possible outcome, known as event states. It is equally important that the event states be both collectively exhaustive and mutually exclusive; that is, each possible outcome must be considered, but must be considered only once. In modeling these uncertain events, probabilities or probability distributions must be used. Sometimes experts can provide the analyst with specific probabilities to apply to each state of an uncertain event, but more often probability distributions must be used. Historical data can be used to select the appropriate distribution for an uncertain event, as well as provide the appropriate distribution parameters.

Values are the results of the decisions and uncertain events which measure the various alternatives. Every possible combination of decision alternatives and uncertain event states in a decision has an associated value. It is by comparing these values that an optimal decision policy is selected. The outcome value is considered the end point of

the analysis. Many times, however, each value has multiple attributes. In this case the decision maker must determine if one attribute is more important than another, if one attribute defines the ultimate objective of the analysis while another defines constraints on the problem, or if the various attributes should be combined in some way to produce a single value.

Model Structure

When modeling a decision problem, there are two primary forms that may be used: the influence diagram or the decision tree.

The *influence diagram* is a very visual method of modeling which represents decisions, uncertain events, and values by different node shapes. The influence diagram is a very intuitive method of modeling, as it has a relatively low level of detail. What it does demonstrate is the influences or effects that exist between each node. An arrow drawn from one node to another indicates that the node at the tail of the arrow, be it a decision, uncertainty, or value, will affect the node at the head of the arrow. In the example influence diagram below (Figure 29), a decision must be made prior to the outcome of the uncertain event being known, and both the decision and the uncertain event affect the end value.

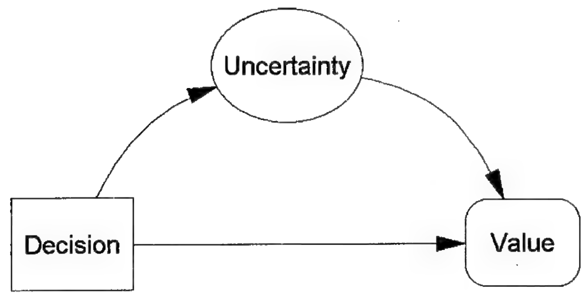

Figure 29. Sample Influence Diagram

The *decision tree*, while still a visual depiction of the problem, allows the analyst to include more detail. The different problem elements are again denoted by the various node shapes, and the problem flow is depicted in how the decisions and uncertain events are ordered. In the example above, however, it is not apparent how many decision alternatives there are or what uncertain event states exist. It is also unclear whether or not the same set of uncertain event states is available for each decision alternative. The decision tree of this same example (Figure 30) depicts the greater level of detail that can be obtained by including the decision alternatives, the uncertain event probabilities, and possible outcome values. It also shows how the decision tree may sometimes provide a more precise representation of the problem.

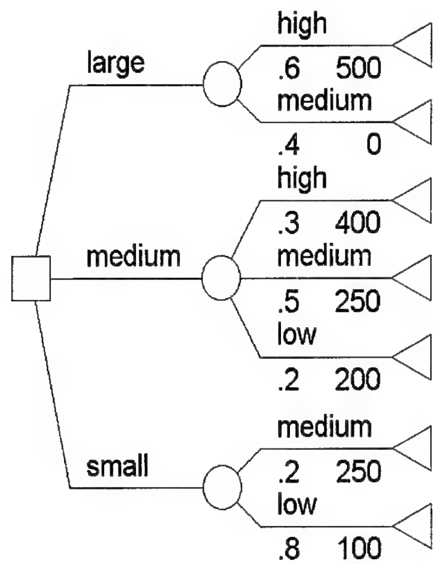

Figure 30. Sample Decision Tree

Appendix B. Model Equations and Values

Waste Generated

Dependent upon Waste Reduction Method and Waste Generation Rate, the total amount of waste generated at WPAFB (tons/year), after de-normalizing the Waste Generation Rate:

$$\textbf{Waste Generated} = ((\textbf{Waste Generation Rate} * 0.3) + 0.5) * \textbf{Base Population} \quad (1)$$

Commercial Waste

The amount of waste generated in the commercial areas of WPAFB (tons/year):

$$\textbf{Commercial Waste} = 0.75 * \textbf{Waste Generated} \quad (2)$$

Residential Waste

The amount of waste generated in the residential areas of WPAFB (tons/year):

$$\textbf{Residential Waste} = \textbf{Waste Generated} - \textbf{Commercial Waste} \quad (3)$$

Commercial Waste Recycled

The amount of commercial waste that is recycled given a selected decision policy (tons/year), 0.75 refers to the expected percentage of waste generated in the commercial areas of base that can be recycled:

$$\textbf{Commercial Waste Recycled} = 0.75 * \textbf{Comm Waste} * \textbf{Comm Recycling Participation} \quad (4)$$

Residential Waste Recycled

The amount of residential waste that is recycled given a selected decision policy (tons/year), 0.65 refers to the expected percentage of waste generated in the residential areas of base that can be recycled:

Residential Waste Recycled = 0.65 * Res Waste * Res Recycling Participation (5)

Commercial Waste Composted

The amount of commercial waste that is composted given a selected decision policy (tons/year), 0.10 refers to the expected percentage of waste generated in the commercial areas of base that can be composted:

Commercial Waste Composted = 0.10 * Comm Waste * Comm Composting Participation(6)

Residential Waste Composted

The amount of residential waste that is composted given a selected decision policy (tons/year), 0.20 refers to the expected percentage of waste generated in the residential areas of base that can be composted:

Residential Waste Composted = 0.20 * Res Waste * Res Composting Participation (7)

Recycling Cost

The total cost that is incurred by operating the various recycling collection methods as well as the actual contracted collection costs:

Commercial Recycling Method : Central	X = 37.5	($ / ton)
Commercial Recycling Method : Satellite	X = 42.5	
Commercial Recycling Method : Commingled	X = 40.0	
Commercial Recycling Method : Separated	X = 42.5	
Residential Recycling Method : Central	Y = 37.5	
Residential Recycling Method : Satellite	Y = 42.5	
Residential Recycling Method : Commingled	Y = 37.5	
Residential Recycling Method : Separated	Y = 42.5	

Recycling Cost = X * Comm Waste Recycled + Y * Res Waste Recycled + Comm Recycling Collection Method Cost + Res Recycling Collection Method Cost (8)

where Commercial and Residential Recycling Collection Method Costs are dependent upon the collection method:

Method	Commercial	Residential	
Central	$0	$0	($ / year)
Satellite	$0	$0	
Commingled	$0	$50,000	
Separated	$0	$75,000	

These costs reflect the actual operating and collection costs for WPAFB and the decision makers' assumptions concerning the costs of changing the policy. Note that these costs are not intended to reflect all costs, but rather show those costs that are captured in the decision maker's budget. Further, while some of these costs may not seem intuitively correct, they do represent the actual costs incurred at Wright-Patterson AFB.

Composting Cost

The total cost that is incurred by operating the various composting collection methods as well as the actual contracted collection cost:

Commercial Composting Method : Central	X = 5.0	($ / ton)
Commercial Composting Method : Satellite	X = 10.0	
Commercial Composting Method : Pickup	X = 5.0	
Residential Composting Method : Central	Y = 5.0	
Residential Composting Method : Satellite	Y = 10.0	
Residential Composting Method : Pickup	Y = 5.0	

Composting Cost = X * Comm Waste Composted + Y * Res Waste Composted + Comm Composting Collection Method Cost + Res Composting Collection Method Cost (9)

where Commercial and Residential Recycling Collection Method Costs are dependent upon the collection method:

Method	Commercial	Residential	
Central	$0	$0	($ / year)
Satellite	$0	$0	
Pickup	$50,000	$50,000	
None	$0	$0	

These costs reflect the actual operating and collection costs for WPAFB and the decision makers' assumptions concerning the costs of changing the policy.

Waste Reduction Level

The percentage of waste that WPAFB can expect to generate, with respect to the 1992 amount, dependent upon the decision policy selected (%):

Waste Reduction Level = 1 - (Waste Generated / Baseline Waste Generation) (10)

Recycle Level

The percentage of waste generated in a year that is either recycled or composted (%):

Recycle Level = (Waste Recycled + Waste Composted) / Waste Generated (11)

Program Profit

The profit, if any, that is realized after deducting the program costs from the revenue generated from recyclable material sales, dependent upon the Waste Reduction Method ($/year), 200,000 refers to the current waste removal contract cost for WPAFB:

Program Profit = (Recycled Materials Price * Waste Recycled) - (Recycling Cost + Composting Cost + Reduction Method Cost + 200,000) (12)

Waste Reduction Utility

The Waste Reduction Level measured in terms of utility to the decision maker

if Waste Reduction Level > 0.5, then Waste Reduction Utility = 1; else, Waste Reduction Utility = -0.0003235 + 0.0003235 * e^(16.07 * Waste Reduction Level)(13)

Recycle Level Utility

The Recycle Level measured in terms of utility to the decision maker

if Recycle Level > 0.5, then Recycle Level Utility = 1; else, Recycle Level Utility = -0.0003235 + 0.0003235 * e^(16.07 * Recycle Level) (14)

Profit Utility

The normalized Program Profit value and associated utility to the decision maker

Profit Utility = (Program Profit + 420,000) / 320,000 (15)

Final Output Value

The overall score of each set of decision alternatives, determined by the weighted utility scores

$$\textbf{Final Output Value} = (0.3 * \textbf{Waste Reduction Utility}) + (0.6 * \textbf{Recycle Level Utility}) + (0.1 * \textbf{Profit Utility}) \quad (16)$$

Waste Recycled

The total amount of waste recycled (tons/year):

$$\textbf{Waste Recycled} = \textbf{Commercial Waste Recycled} + \textbf{Residential Waste Recycled} \quad (17)$$

Waste Composted

The total amount of waste composted (tons/year):

$$\textbf{Waste Composted} = \textbf{Commercial Waste Composted} + \textbf{Residential Waste Composted} \quad (18)$$

Base Population

The 1996 base population at WPAFB:

$$\textbf{Base Population} = \textbf{21,000} \quad (19)$$

Baseline Waste Generation

The amount of waste generated in 1992 (tons):

$$\textbf{Baseline Waste Generation} = \textbf{17,000} \quad (20)$$

Beta Distribution Parameter Calculations

The average participation and normalized waste generation rates used in the model are shown in Tables 3 and 4, respectively. These average values have been used to calculate the appropriate parameters (a,b) for use in the beta distribution for the uncertainty nodes "Commercial Recycling Participation", "Residential Recycling Participation", and "Waste Generation Rate". Those parameters were calculated as follows:

$$\mathbf{a >= 1,\ b >= (a + 1)} \qquad \textbf{(parameter constraints)}$$

$$\mathbf{mean = a / b} \qquad \textbf{(21)}$$

$$\mathbf{variance = (a / (b * (1 + b))) * (1 - mean)} \qquad \textbf{(22)}$$

$$\Rightarrow \mathbf{variance = ((mean * b) / (b * (1 + b))) * (1 - mean)}$$

$$\Rightarrow \mathbf{variance = (mean * (1 - mean)) / (1 + b)}$$

Therefore, because the mean is known, the variance is maximized when b is minimized, so let **b = a + 1**. Then,

$$\mathbf{mean = a / (a + 1)}$$

$$\Rightarrow \mathbf{a = mean / (1 - mean)} \qquad \textbf{(23)}$$

However, if mean < 0.5, this yields a value of a < 1, and the parameter constraints are violated. Because the maximum variance is achieved at the minimum b, and b = a / mean (from Equation 21), the minimum b is realized at the minimum a, so let **a = 1,** and

$$\mathbf{b = 1 / mean} \qquad \textbf{(24)}$$

Using this information the parameters for these three uncertainty nodes are:

Table 8. Beta Parameters for Commercial Recycling Participation

Commercial Recycling Collection Method

	Central	Satellite	Commingled	Separated
mean	0.47	0.57	0.78	0.62
a	1.000	1.326	3.545	1.632
b	2.128	2.326	4.545	2.632

Table 9. Beta Parameters for Residential Recycling Participation

Residential Recycling Collection Method

	Central	Satellite	Commingled	Separated
mean	0.42	0.52	0.73	0.57
a	1.000	1.083	2.704	1.326
b	2.381	2.083	3.704	2.326

Table 10. Beta Parameters for Waste Generation Rate

Source Reduction Method

	None	Equipment	Regulation	Education	Combination
mean	0.767	0.567	0.467	0.367	0.167
a	3.286	1.308	1.000	1.000	1.000
b	4.286	2.308	2.143	2.727	5.988

Recycled Materials Price

The recycled materials price is calculated using a normal distribution. The mean value is 50 and the standard deviation is 15. The value is measured in $ per ton.

Reduction Method Cost

The cost for the various source reduction methods were defined by the decision makers. They represent the least, most, and average amount of funding that would be allocated towards the denoted source reduction methods. The probability of each value is approximated using the Pearson-Tukey method (Clemen, 1991: 220). Table 11 shows the low, medium, and high values for each method. Recall that the Pearson-Tukey method applies a probability of 0.185 to both the low and high values and a probability of 0.63 to the medium value.

Table 11. Reduction Method Costs

Source Reduction Method

	None	Equipment	Regulation	Education	Combination
low	---	5,000	5,000	20,000	30,000
medium	0	10,000	10,000	50,000	70,000
high	---	20,000	20,000	100,000	140,000

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13. ABSTRACT *(Maximum 200 words)*

The United States Air Force has recently defined three objectives in developing strategies regarding the management of municipal solid waste at the base level. They are: (1) 50 percent reduction in total waste generated, from a 1992 baseline amount, by 1999; (2) 50 percent recycling of all waste generated, beginning in 1999; and, (3) a minimum cost program. With these objectives in mind, base environmental engineers must take appropriate actions in an effort to develop a program that meets these goals. Through consultations with base environmental managers, as well as research of the available literature, a decision support model was constructed to aid the decision maker in selecting a program that shows the best performance relative to these objectives. This model considers decisions regarding waste collection methods, waste reduction methods, and waste incineration. Sensitivity analysis is used to determine the most important variables in the model. Finally, the model and resulting analysis provide the decision makers with valuable insight concerning the selection and implementation of a municipal solid waste management policy.

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